**US Army Corps
of Engineers**
Waterways Experiment
Station

Computer Automated Chamber Test System

by   Paul A. Gilbert, Terry V. Jobe

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U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS   39180-6199

Final report

US Army Corps of Engineers
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PUBLIC AFFAIRS OFFICE
U.S. ARMY ENGINEER
WATERWAYS EXPERIMENT STATION
3909 HALLS FERRY ROAD
VICKSBURG, MISSISSIPPI 39180-6199
PHONE: (601) 634-2502

SCALE
500   0   500 m

AREA OF RESERVATION < 2.7 sq km

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Preface

The study reported herein was conducted by the Geotechnical Laboratory (GL), U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, for Headquarters, U.S. Army Corps of Engineers (HQUSAE). The work was performed under the Civil Works Research and Development (CWR&D) program under Work Unit 32676, Laboratory Determination of Soil Properties.

This study was conducted under the general supervision of Dr. W. F. Marcuson III, Director, GL, and Dr. Don Banks, Chief, Soil and Rock Mechanics Division (S&RMD), GL. The report was produced under the direct supervision of Mr. Robert D. Bennett, Chief, Soils Research Center (SRC), GL. Mr. Al Branch was the HQUSACE Technical Monitor.

This report was prepared by Mr. A. Paul Gilbert, SRC, with computer programming and instrumentation by Mr. Terry V. Jobe, SRC. Significant support in instrumentation and logic circuitry was provided by Mr. Thomas V. McEwen, Instrumentation Systems Development Division (ISDD), now retired.

The study has produced two patented products, a logic valve that responds to computer control, U.S. Patent number 5,178,361, and a high vacuum rotating seal assembly, U.S. Patent number 5,472,215. Additionally, a patent has been applied for a modified version of the logic valve, Corps of Engineers (COE) file number 436.

During this investigation, Dr. Robert W. Whalin was the Director of WES. COL Bruce K. Howard, EN, was the Commander.

Conversion Factors,
Non-SI to SI
Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic inches	16.38706	cubic centimeters
degrees (angle)	0.01745329	radians
Fahrenheit	5/9	Celsius degrees or Kelvin[1]
feet	0.3048	meters
foot-pound (force)	135.5818	joule
inches	2.54	centimeters
inch-ounces	141.6119	newton-meter
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.4535924	kilograms

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9) (F-32)$. To obtain Kelvin (K) readings, use: $K + (5/9) (F-32) + 273.15$.

1 Introduction

General

One of the purposes of this investigation was to develop equipment to perform computer-automated chamber tests. A chamber test, as used herein, is defined as a soil test in which a specimen is enclosed in a rubber (or polymeric) membrane, then placed inside a closed vessel/chamber where it is subjected to hydrostatic and/or deviatoric[1] stresses with controlled drainage. An integral part of any chamber test configuration is a plumbing/piping system that allows controlled application of pressure or vacuum and water flow to remove entrapped air/gas from the void space of a test specimen and achieve (water) saturation.

Tests to determine consolidation/compression characteristics, permeability, and (shear) strength in any combination may be performed in the pressurized chambers described in this report. A schematic of the system developed in this research is shown in Figure 1. The system consists of a computer-controlled and software-driven pressure and force application system. The hardware is configured so that a general chamber pressure test can be conducted with the equipment by including or excluding the function of various components of the system, that, when not used or required, can be excluded by closing appropriate shutoff valve(s).

In performing a chamber test, a technician applies a sequence of controlled pressures and forces to a soil specimen by opening and/or closing valves in reaction to response observed in the specimen. Chamber tests are extremely labor- and time-intensive when performed manually; therefore, automating such a test with computer control is a practical and sensible step because of potential labor and time savings. The conduct of a chamber test proceeds in an orderly sequence of steps, and a computer can be programmed to control any procedure that can be precisely described. Through electronic sensors, a computer can recognize events, can control an operation precisely, can use programmed logic to determine the beginning or end of a process, and can open and close valves in response to a recognized event.

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[1] *Deviatoric* or *deviator stress* as used in this report is defined as the ratio of the effective axial force to the area of the specimen projected in a plane perpendicular to the axial direction.
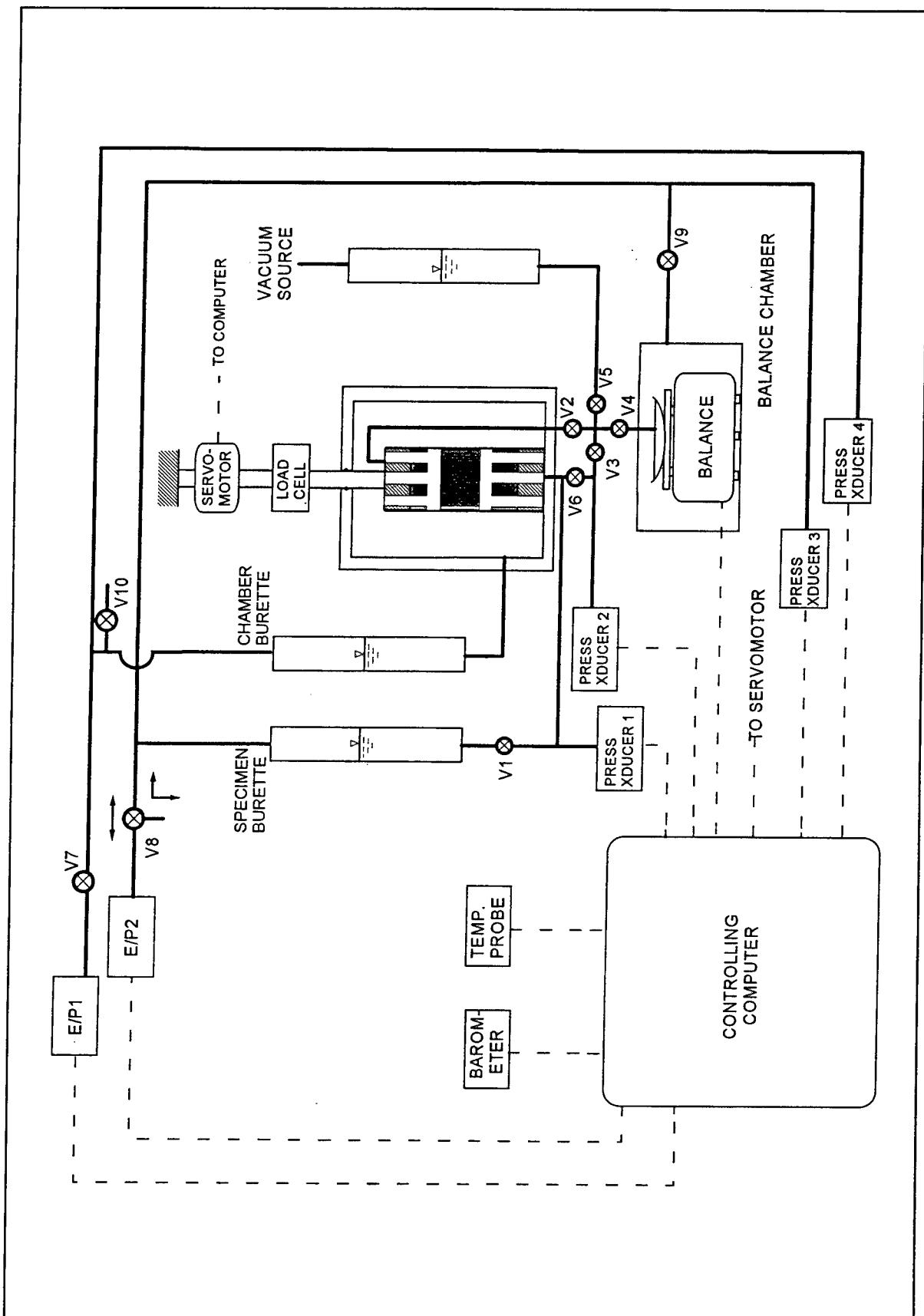
Figure 1.   Schematic of computer-automated testing system

Certain important advantages can be gained by automating a chamber test or any laboratory soil test by programmed control. The most obvious advantage is that a technician is released from a time- and labor-intensive task to do other work. Other advantages are also evident. For example, in most instances a chamber test requires more than one day to set up and perform. In such a case, the time that a test specimen and associated equipment sit idle during off-hours may be more than simply an unproductive period; soil properties that will be measured in the test may actually be affected by long lapses or delays between operations. If a triaxial test specimen finishes primary consolidation shortly after office hours, it will be subject to 16 or more hours of secondary compression before the next step is initiated. Such a delay in testing could ultimately affect the strength (or permeability) of a specimen as well as diminish test productivity. Therefore additional advantages of automation are that test production will likely be enhanced, and tests will be performed consistently and with a uniform time progression as the result of computer automation. Uniformity in test performance is important since variations in testing procedure may affect results.

It must also be realized that the skill, experience, and patience of laboratory technicians vary widely; the result is that measured values of soil properties determined from a laboratory test may be a function of the technician who performs a particular test. In this light, the advantage of computer automation is clear in terms of the consistency it affords. After a technician trims and places a specimen into the test chamber of the equipment developed in this investigation, control of the test is transferred to the computer, and the system requires no further manual assistance. Each step of the test is performed in sequence directly following the preceding step with the reliability and consistency of software control. In this way, the human element and operator influence is removed from the process to the maximum possible extent.

The easy availability of certain appliances from the commercial sector made developing this equipment economically practical and technologically feasible. The appliances are (a) a computer with signal conditioning electronics, (b) voltage to pressure transducers, and (c) a computer-driven servomotor system. A component necessary for the system that was not available from the commercial market is a ball valve system remotely controllable by computer command. Each of these components will be described below.

Computer

The availability of inexpensive and reliable small computers makes the development of equipment like that produced in this investigation feasible. International Business Machines (IBM) published technical specifications for several models of personal computers in the open literature in the early 1980s. As a result, vendors from the private sector responded with IBM clones and compatible personal computers, as well as a variety of interface peripherals for use with these machines. Because of the widespread availability of IBM computers and clones, as well as peripherals for communication with and control over outside appliances, the IBM system was chosen for use in the equipment under development. An AT class IBM computer with 640 kilobytes of random

access memory (RAM) controls the procedures of the chamber tests satisfactorily through specially prepared software. Data acquisition and reduction are desired along with control and performance of the test, so a 20-megabyte hard disk (minimum) is required for the software to execute properly. The software and the equipment to control the process will be discussed and described in detail next.

Signal Conditioning

An internal printed circuit board (installed in one of the slots provided in the computer) called a UPC607 Universal PC Interface Card, manufactured by the Validyne Engineering Corporation of Northridge, CA is used as part of the equipment. This board is convenient in that it provides:

a. Signal conditioning for up to 8 differential or 16 single-ended sensors.

b. Analog-to-digital (A/D) conversion of the input signal from the sensors.

c. Analog outputs for controlling voltage-driven appliances.

d. Digital outputs for controlling logic-driven devices.

The functions of this board are controlled through software written in the BASIC language by CALLs to SUBROUTINEs.

Voltage-to-Pressure Transducers

Voltage-to-pressure transducers are devices that take voltage signals from the controlling computer as input then output extremely precise air pressure levels in response. The transducers are manufactured by the Bellofram Corporation of Newell, WV. These devices are, effectively, computer/logic-controlled pressure regulators; the model used in the present system has a span from 0 to 100 psi. The pressure that is output by the transducer is regulated with a proportional, integral, derivative (PID) analog electronic controller which provides precision pressure control. The transducer manufacturer guarantees accuracy to within ±0.25 percent (of full span) in the published specifications for the device, which in the case of a 100-psi transducer is ±0.25 psi. However, the statement is also made in the specifications that accuracy is typically ±0.1 percent of full span. A careful calibration of these transducers using a source readable to 0.002 psi (and traceable to the National Bureau of Standards) showed that transducer output pressure accuracy was ±0.1 percent, and often better.

Voltage-to-pressure transducers are used in this system to apply and control the chamber pressure and back pressure in response to software commands. Their location in the system can be seen in the schematic of Figure 1; they are

designated E/P1 and E/P2 for the chamber pressure and back pressure trans-
ducers, respectively.

Computer-Controlled Ball Valves

An integral activity in performing any chamber test is opening and closing
valves on cue. Since computer automation is the object of the system under
development, ball valves[1] that operate remotely under computer control are
necessary. However, a search of commercially available products did not
locate an acceptable logic-controlled valve system. Consequently a computer-
controlled ball valve system was designed and constructed at the U.S. Army
Engineer Waterways Experiment Station (WES). The computer-controlled
valve developed is described in detail below. It should be noted that
valves V1 through V6 are computer controlled (see Figure 1). Valves V7
through V10 are manual, and used during the phase of the test where the speci-
men is loaded in the chamber and the equipment is prepared for computer soft-
ware control.

Servomotor

A servomotor system was selected for this application rather than a stepper
motor because of the additional speed and versatility available with the servo-
system. The servomotor system is described in detail in Chapter 3.

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[1] Valves that open and close with no volume displacement.

2 Volume Measurement in Saturated Specimens

General

An electronic laboratory balance is used to measure the (mass and therefore) volume of water discharged from a specimen during consolidation and shear (in the case of a drained triaxial compression test) or volumetric flow rate through a soil specimen during a permeability test. Use of a laboratory balance in connection with testing equipment of this nature is advantageous for many reasons, notably, great precision in volumetric flow measurement can be achieved. Integration of modern digital balances into a logic-controlled system like the present equipment is uncomplicated, since they are designed for communication and compatibility with personal computers. However, in use, the balance must operate inside a pressurized chamber for the proposed application, and there are complications associated with this service because buoyancy increases as pressure (and therefore density) increases. These problems were explored and resolved, and the mathematical development associated with the solution is shown below in detail. The balance, as used in this system, is shown schematically in Figure 1, where it is seen that the device is contained in a pressure-tight vessel. The pressure inside that vessel will be the output of the voltage to pressure transducer, E/P2, the device that controls and applies back pressure. It should be noted that the tube that delivers water discharged from the specimen into the pressurized chamber extends below the water surface in the pan that sits on the balance. Therefore, the energy of water being discharged from the tube dissipates in the volume of water already in the pan, thereby preventing the possibility of water splattering out of the pan during a test. Additionally, a thin film of oil is used to cover the surface of water in the pan to prevent evaporative water loss with time.

Balance Operation and Use

Water mass can be measured precisely with a laboratory balance; for example, the balance selected for the system under consideration is a Mettler (BB2400 series) balance that has a maximum capacity of 2,400 g mass and a readability and repeatability of 0.01 g. The indication, then, is that a discrete volume of approximately 0.01 ml of water can be identified using this device.

Measurement of water volume in laboratory soil testing to within ± 0.01 ml is considered great accuracy relative to that generally obtained by manually reading a burette (or even by sensing the height of water in a calibrated burette with a pressure transducer). Additionally, the volume capacity of a system based on this (Mettler) balance is approximately 2,400 ml, a relatively large volume compared with that normally available using a burette. Another advantage gained by using a balance capable of sensing small quantities is that low flow rates may be observed and accurately quantified in relatively short periods of time compared to other flow/mass observation techniques where a large volume must be discharged for precise quantification.

Modern digital balances, in general, and the Mettler BB2400 in particular, are designed to be interfaced with a computer (for example, via RS-232C data interface). The balance can be controlled via the RS-232C link and can transmit both status information and data in response to computer commands. For example, on signal from a controlling computer, the balance reading can be nulled to zero, and the balance calibrated and placed in measurement condition where, in response to a query, data consisting of the current reading on the balance are sent to the computer over the RS-232C serial link. It is appropriate to mention that mass/flow data acquired in this manner have excellent immunity to electrical noise because of the precision built into the balance.

A potential problem with the particular balance used in this study is that it cannot be powered up remotely by computer command since a hard-wired mechanical switch is used to control power supplied to the unit. The balance is designed so that if electrical power is interrupted, the system will have to be reactivated by manually resetting the power switch. This was determined to be a great disadvantage since the balance will be contained and operated inside a closed pressure chamber where (in the testing mode) internal pressure is equal to the back pressure applied to the soil specimen to achieve water saturation. Without electronic modification of the balance, if power interruption were to occur during a test, pressure in the chamber would have to be released and the chamber opened to gain access to the balance in order to reset the power switch. This problem was solved by bypassing and thus defeating the power switch such that the balance is always under power. Modified in this manner, power interruption simply causes the (current) reading on the balance to be reset to zero. Additionally, with the modification to the electronics, the balance can be calibrated only electronically through the computer; however, this presents no special problem since (for this study) the balance is always under computer control and a special subroutine was prepared for automated calibration.

After electronic modification, the balance was calibrated (for linearity) with National Bureau of Standards Class S-1 calibration weights. Data observed during calibration carried out under ambient atmospheric conditions (i.e., no elevated pressure applied to the balance) demonstrated close agreement between balance reading observed and calibration mass. However, when a given mass was placed on the platen of the balance and the balance/mass system enclosed in the chamber and pressurized, the indicated mass reading changed as pressure was increased. Additionally, the balance reading changed as a function of pressure in the chamber when no mass was placed on the platen, and mass

indicated by the balance while under pressure was different depending on whether the test substance was steel or water. It was determined that this seemingly aberrant behavior observed in the system could be explained and taken into proper account by consideration of air buoyancy and the internal construction of the balance.

Air Buoyancy Development

The basic internal configuration of the Mettler BB2400 is shown schematically in Figure 2. The system consists, basically, of a lever and a counterbalance mass that is connected to the stem of the electronic force sensing mechanism. The counterbalance mass acts through the lever and pivot to oppose and counter the force that would otherwise be indicated by the (force sensing) mechanism. The counterbalance mass has a certain volume that is the source of most of the unexpected behavior in mass measurement made under elevated air pressure. The pertinent summary of forces acting in the counterbalance system is shown in Figure 3. The force caused by the counterbalance mass is shown as F_m on the diagram and is given by the equation

$$F_m = V_m \left(\gamma_m - \gamma_a \right) \tag{1}$$

where

F_m = force applied by the counterbalance mass

V_m = volume of the counterbalance mass

γ_m = density of the counterbalance mass

γ_a = density of air

As pressure in the chamber increases, density of air, γ_a, increases inside the chamber. As a result, F_m decreases because of increased air buoyancy as air inside the chamber is compressed and therefore densified (see Equation 1). As the force F_m decreases, equilibrium of forces and balance of moments require that F_b, the force applied to the balance mechanism by the lever arm, increase (see Figure 3). This is, in fact, the behavior that was observed in the balance as pressure in the chamber increased. With the balance nulled (and no mass on the platen), as pressure is slowly increased from atmospheric pressure to 100 psi g, the reading on the balance increased from 0 to 1.52 g. From this information, the effective volume and density of the counterbalance system can be quantified.

A simple but adequate formulation for the density of (dry) air as a function of pressure derived from the equation of state for a perfect gas is

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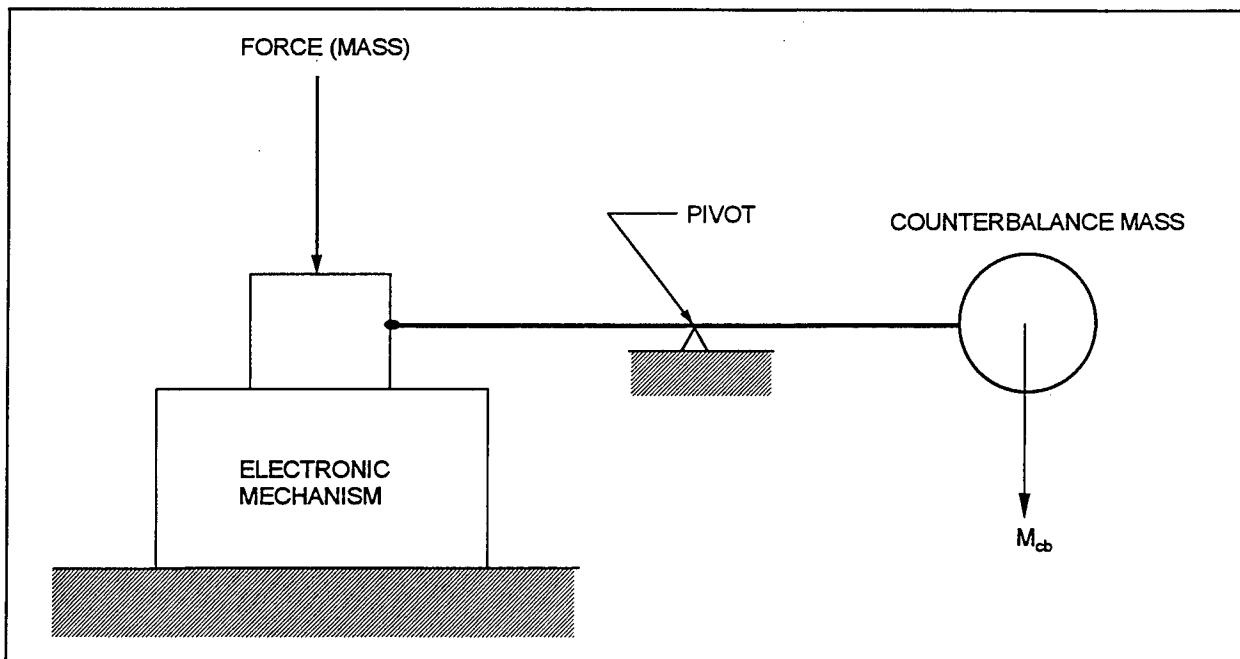
Figure 2.   Schematic of Mettler BB2400 internal configuration showing counterbalance mechanism

$$F_m = V_m (\gamma_m - \gamma_a)$$

F_b = force applied to balance mechanism
F_m = force applied by counterbalance mass
V_m = volume of counterbalance mass
γ_m = density of counterbalance mass
γ_a = density of air
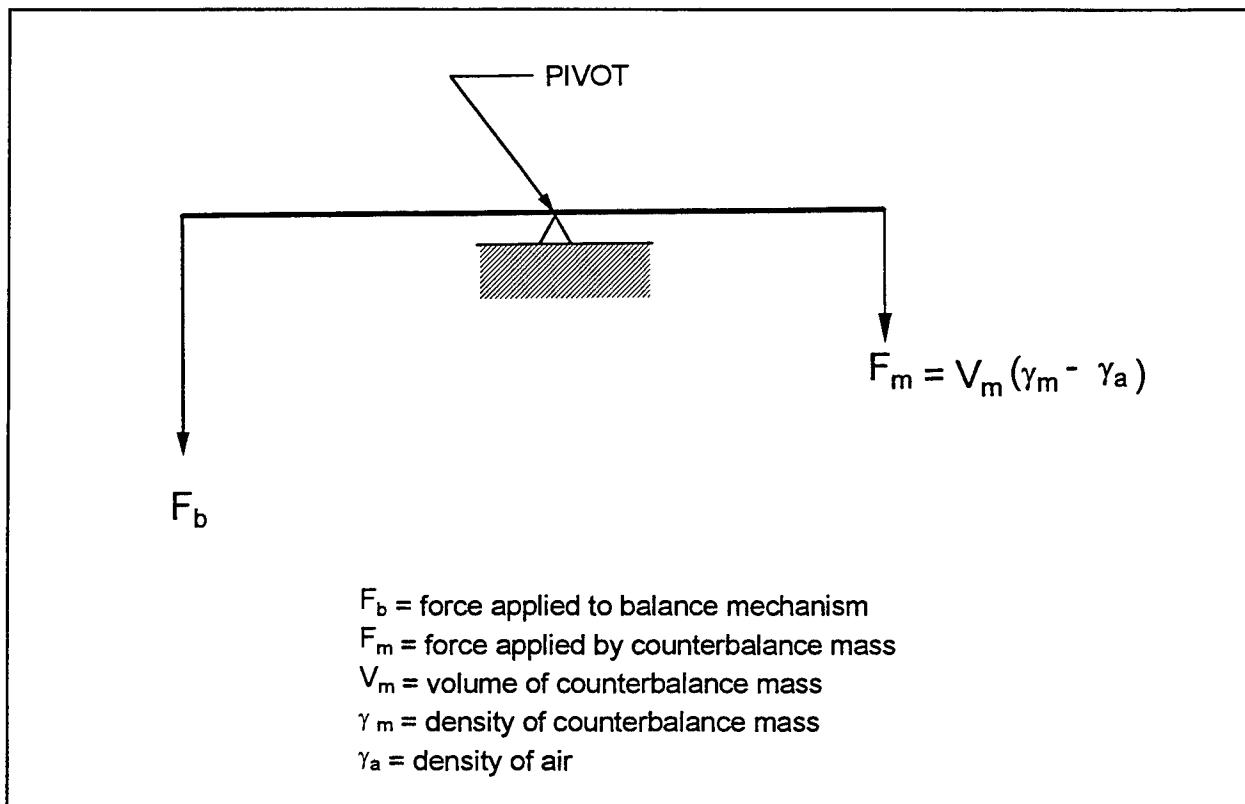
Figure 3.   Forces acting within the balance system

$$\gamma_a = \frac{(P_g + P_m)}{R_a (F + 459.6)} \frac{144}{62.427}$$

(2)

where

γ_a = air density in g/ml

P_g = gauge pressure inside the chamber (psi)

P_m = local atmospheric pressure (psi)

R_a = gas constant for (dry) air

= 53.34 (ft-lbf)/(lbm-°R)

F = chamber/ambient temperature in degrees Fahrenheit

This formulation neglects the effect of humidity because air is dehumidified by a refrigeration air drier before it enters the chamber; the dew point of the air is thus reduced to between 32 and 40 °F. Additionally, humidity has a small influence on the density of air at normal temperatures. For example, increasing the relative humidity of air at 80 °F to 100 percent decreases the mass density of the mixture by about 1 percent; the ratio of the mass of water vapor to the mass of dry air in this mixture is 0.02.

Based on Equation 2 and calibration of the change in mass indicated by the balance (with no mass on the balance platen) as pressure increased, the equation

$$R_o = -0.223 + \gamma_a(186.287)$$

(3)

is determined, where

R_o = balance reading with no mass on platen

γ_a = air density in g/ml (from Equation 2)

The (numerical) constants appearing in Equation 3 are associated with the effective mass and density of the counterbalance mass and platen system along with the geometry and construction of the lever; these constants will be different for each balance and must be determined by calibration under pressure. It is important to note that the platen (that is, the configuration of the pan and mass containment system) on the balance must be the same during testing as that used during the (no mass) pressure run-up calibration. The reason is, of course, that a given pan system has a certain mass and volume to effect specific buoyancy characteristics. Therefore, these buoyancy characteristics must be reflected in the elevated pressure calibration. If another pan system is

substituted or if the calibrated pan system is modified, errors in the mass/volume relationship measured by the balance will result.

Equation 3 contains only the reaction of the "hardware" of the balance to pressure change. The effect of adding mass to the balance must be superposed on Equation 3 and the effect of buoyancy also taken into proper account in that development. Since water is the primary material of interest in the procedure, the equations produced will be customized with the characteristics of water. If Equation 3 is generalized to include the effect of adding an arbitrary mass to the balance, it becomes

$$R_m = -0.223 + \gamma_a (186.287) + V_w (\gamma_w - \gamma_a) \tag{4}$$

where

R_m = mass/reading indicated by the balance

V_w = volume of the substance on the balance (water)

γ_w = density of the substance on the balance (water)

The parameter of interest in Equation 4 is not the associated mass of water but rather the volume of water, V_w; therefore, Equation 4 is rearranged to yield

$$V_w = \frac{R_m + 0.2233791 - \gamma_a(186.2869569)}{(\gamma_w - \gamma_a)} \tag{5}$$

Density of water is a function of temperature and must be properly considered. The equation describing the variation of water density with temperature (determined by curve fitting) is

$$\gamma_w = aF^5 + bF^4 + cF^3 + dF^2 + eF + f \tag{6}$$

where

$a = 6.733786E\text{-}14$ $b = -5.301964E\text{-}11$ $c = 1.779546E\text{-}8$

$d = -4.007605E\text{-}6$ $e = 2.430838E\text{-}4$ $f = 0.9956743$

F = temperature in degrees Fahrenheit.

The units of γ_w in Equation 6 are grams per milliliter (g/ml) and values determined from the equation over the range 32 °F to 212 °F (0 °C to 100 °C) match precisely those given in the *Handbook of Chemistry and Physics* (1958). The density of air for use in Equation 4 may be obtained from Equation 2. In an effort to be correct and consistent, units of g/ml have been used throughout this treatment. However it should be noted that g/ml and g/cm^3 may be used

interchangeably with little loss in accuracy since 1 ml is equal to 1.000027 cm^3.

Equation 2 contains the term, P_m, that is the local atmospheric pressure. This term is a combination of the local barometric pressure and the elevation above sea level, since the equipment under development is intended for general use at any location (and elevation). An expression was developed to give accurate values of local atmospheric pressure, P_m, taking elevation and local barometric pressure fluctuations into account. The expression is

$$P_m = P_b \left(\frac{14.696}{29.92} \right) e^{-3.61226523 \times 10^{-5} Y} \tag{7}$$

where

P_b = local barometric pressure in inches of mercury

Y = local elevation above sea level in feet

Equation 7 takes the fact that the atmosphere is a mixture of compressible gases into account. The entire treatment presented assumes dry air; the consequences of water vapor in the atmosphere were omitted because (a) the compressibility and density characteristics of air would not be changed significantly (about 1 percent) by their inclusion, (b) it would substantially increase the complexity of the treatment, and (c) complete quantification would require values of parameters that are generally unavailable and difficult to measure.

It should be noted that the hardware system contains a built-in sensor for measuring and acquiring local barometric pressure that only needs an initial setting. The elevation of the local site (in feet) must also be entered into the software code upon placement and initialization of the system. These values need not be altered again unless and until the equipment is moved to a different location/elevation. Fluctuations in barometric pressure will not cause serious errors in parameters measured during a laboratory soil test. However, since the equipment in this system is under automated computer control and since local pressure fluctuation is a systematic error that can be easily and inexpensively taken into consideration by software, it was decided to account for and correct this error. In a similar manner, ambient temperature is an important environmental variable in (equations describing and recounting) the procedure. Temperature is sensed and acquired automatically through an electronic transducer (thermistor) built into the system. Pressure and temperature data are acquired as functions of time during the course of a test. The electronic temperature probe is inserted in a (covered) vessel of water placed in the vicinity of the test apparatus. In this way, fluctuations in the temperature of water are sensed and accounted for, since the density of water is significantly affected by temperature variation. Failure to properly account for density changes as the result of temperature fluctuation could result in errors in volume measurement.

Based on the models developed and presented, the software takes air buoyancy, temperature fluctuations and their influence, on water density as well as changes in atmospheric pressure and the elevation of the site into proper account.

3 Force Control and Application System

It is necessary to regulate the application of force in the automated system remotely and by computer command to achieve automated control of the test procedure. Several operations in a pressure chamber test require regulated force control, among which are pressure uplift correction and axial loading in either the controlled stress or strain modes. Each of these cases will be described below along with the procedure used for force control and the mathematical development associated with and necessary for each case.

Force Control System

The force application system used in the automated equipment consists of a computer-controlled servomotor (with its accompanying encoder, software, and power circuitry), a supporting structure (frame), and a ball screw in the arrangement shown in Figure 4. Computer command of the force system is achieved with a digital PID filter that is used to compensate the control loop. Software performs all the computational tasks required for digital motion control, and both position and velocity control are possible in the present system. In position mode, the host processor specifies acceleration, maximum velocity, and final position; in velocity mode, the motor accelerates to the command velocity and maintains that velocity until a new command is given. The process is driven by either velocity, force, or displacement as electronic feedback. The controller drives the motor (either forward or backward) through an electronic power network until the required prespecified condition is satisfied. The motor contains a built-in encoder, and actual motor position is monitored by sensing the output of that encoder. Position error during control is processed through the (PID) filter to drive the motor. Force or displacement requirements are monitored and controlled in terms of the electronic signal from a force or displacement (linear variable differential transformer, LVDT) transducer. Required axial velocity is achieved by specifying a motor speed that acts through the ball screw to achieve constant axial velocity. One of the features built into the (servo) controller is to enforce constant motor speed that is required for a constant rate of (axial) strain test.
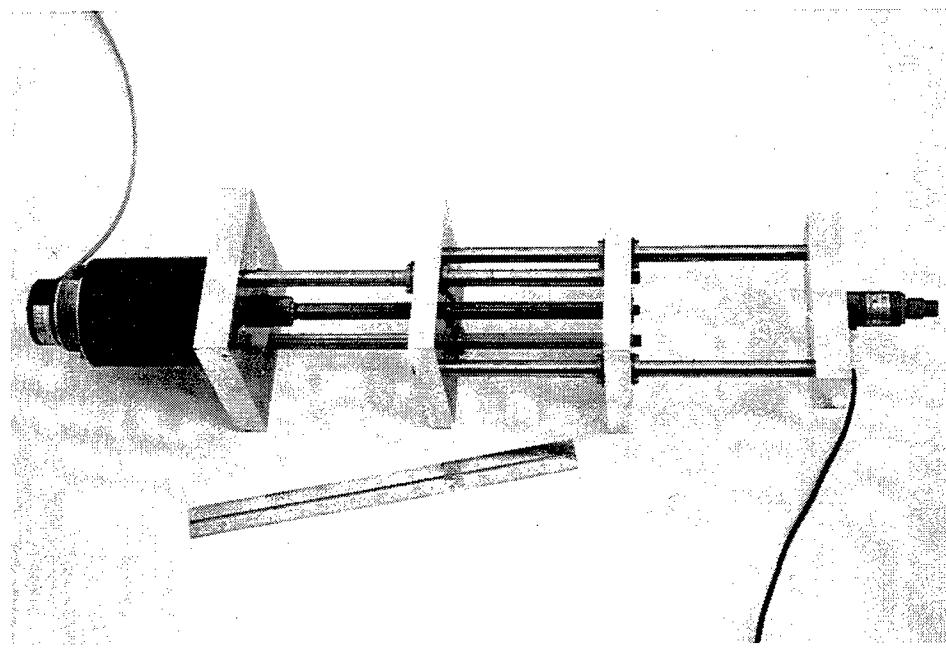
Figure 4.   Motor-ball screw assembly

A ball screw is a threaded shaft and nut assembly in which the nut rides on roller bearings along the helical thread of the shaft. Extremely low friction is achieved with a ball screw configuration because rolling friction is effected instead of sliding friction, and rolling friction is substantially less than sliding friction. Therefore, considerably less energy is lost in a ball screw mechanism as compared to a conventional nut and screw. In the actuator designed and built for use with the present system, a (servo) motor drives a ball screw through a stationary nut to apply required force or displacement to the specimen. The relationship between thrust generated by a motor with a given torque capacity acting through a threaded shaft/nut assembly is

$$F_r = 2 \pi T N e \tag{8}$$

where

F_r = thrust/force generated by the system

T = torque capacity of the motor

N = number of threads per unit length of shaft

e = efficiency of the nut/screw system

The efficiency, e, of the system is directly related to friction between the nut and the shaft. For sliding friction, even between a well lubricated nut and shaft, efficiency could be as low as 0.2 to 0.3, which means that 70 to

80 percent of the energy delivered by the motor is lost to friction. However, in a ball screw, efficiency is typically 0.9, and some manufacturers of ball screws state an efficiency that is as much as 0.95 in their specifications. For example, the servomotor used in this investigation produces a maximum torque of 170 in.-oz; when coupled with a ball shaft that has 1 thread per 2 mm and an efficiency of 95 percent, then by Equation 8, the maximum thrust is about 800 lb.

Obviously, thrust generated is maximized by maximizing each term in Equation 8. The term N represents the number of threads per unit length of shaft. This term like all others in the expression is direct, so increasing its value increases the thrust developed. However, it must be realized that N cannot be increased indefinitely; increasing the number of threads per unit length of shaft decreases the load-carrying capacity of the threads (due to limiting shear strength of the shaft material). Generally, the smaller the value of N, the greater the load-carrying capacity of the shaft. Also, it must be realized that the system will be under digital control and values of N that are too small will result in a loss of system performance in terms of the amount of deformation that can be applied (in one digital increment). The smallest axial movement possible because of digital control in terms of the number of threads per unit length, N, is

$$\Delta = \frac{\gamma}{(2 \pi N)} \qquad (9)$$

where

Δ = smallest axial displacement possible

γ = smallest motor rotation (in radians) possible (as the result of digital control)

In terms of degrees, Equation 9 may be rewritten

$$\Delta = \frac{\gamma}{(360 N)} \qquad (10)$$

where γ in Equation 10 is given as degrees of rotation.

If the stiffness of a specimen under test is large, then it is necessary to achieve control by applying small amounts of deformation; otherwise, the increment of force controllable with the system will be large. In such a case, violent instability may result because the amount of force that *must* be controlled is less than the amount of force that *can* be controlled with the result that the system will not be able to "find" the force necessary to satisfy the control equations and will search continuously. The selection of N is therefore a balance between maximizing the thrust that can be developed by the components of the actuator, and maximizing system control in terms of the smallest

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amount of deformation (and axial force) that can be applied in one digital increment.

Uplift Force Correction

Because the load piston is rigidly attached to the top platen in the test configuration of the present system, it is necessary to apply an uplift piston force correction. A pressure, σ_3, applied inside the chamber does not act over the entire surface of the specimen; an area, A_p, on the top of a circular cylindrical specimen is excluded from pressure application. With the rigid connection between piston rod and platen, hydrostatics and the requirement for equilibrium dictate the need for a complementary piston force given by the expression

$$F_u = \sigma_3 A_p - W_p \tag{11}$$

where

F_u = complementary uplift force

σ_3 = gauge pressure inside chamber

A_p = area of piston rod leaving the (sealed) chamber

W_p = weight of the piston rod acting/resting on the specimen

The uplift force computed from Equation 11 is the force necessary to complete the hydrostatic stress condition on the specimen in the axial/vertical direction. Without this force, pressure applied to the chamber will result in a deviator stress applied to the specimen (with the stress in the axial direction being the smaller principal stress). Depending on the magnitude of the chamber pressure and the piston area, deviator stress applied in this manner could be of sufficient magnitude that the soil specimen experiences significant tensile strain or even fails in extension (in the axial direction). It should be noted that axial extension tests are sometimes performed by deliberately increasing the chamber pressure in test configurations where the piston is connected to the top platen. Obviously if the area of the piston leaving the seal, A_p, were zero, or the piston is not connected to the top platen, pressure applied to the chamber would result in a pure hydrostatic (isotropic) stress applied to the specimen and uplift force correction would be unnecessary.

Chamber pressure is increased during saturation and consolidation in a triaxial compression test specimen that is saturated by the application of back pressure. During saturation and consolidation, it is critically important to correct for pressure uplift to avoid inadvertently stressing and damaging the specimen as well as to measure important test parameters correctly. For example, checking specimen saturation by determining Skempton's "B" parameter (Skempton 1954) could result in an incorrect and misleading conclusion if

proper uplift correction force is not applied during the "B" parameter pressure increase. This effect will be discussed in detail below.

Atmospheric Pressure Measurement

Atmospheric/barometric pressure was measured with an 1,800 series Foxboro pressure transducer. The 1,800 series transducer utilizes a piezo-resistive silicon element for pressure measurement. In its construction, resistors are implanted on a silicon diaphragm and connected to form a Wheatstone bridge. The diaphragm is formed by etching the silicon below the resistors. As pressure is applied to the diaphragm, the resistors change in value to produce an essentially linear output proportional to the applied pressure.

The Foxboro 1800 transducer used in the present application is an absolute pressure gauge, so it was necessary to calibrate the device in a vacuum chamber. The transducer was determined to be highly sensitive and accurate. After calibration, the Foxboro 1800 was monitored for a week by comparing the atmospheric pressure indicated with that of a reliable aneroid barometer. The comparison showed that fluctuations in atmospheric pressure level indicated by the Foxboro 1,800 corresponded precisely with that indicated with the aneroid barometer.

4 Computer-Controlled Ball Valve for Laboratory Automation

General Purpose

In laboratory soil testing and certain other laboratory processes, it is necessary to open and close lines/tubes in a piping/plumbing system with no resulting volume displacement. In laboratory soil testing, for example, the piping system is often water saturated and of low compliance (high stiffness) such that volume displacement associated with the operation of normal valves will cause pressure surges and fluctuations in the system that may alter specimen behavior, corrupt measured constitutive properties data, and invalidate the test. Additionally, under certain conditions, sensitive electronic measurement devices used in the plumbing system could be damaged or destroyed by valves in the system that displace a minute volume during use. For this reason, ball valves are used for soils and other critical laboratory testing where volume displacement control is critical and in hydraulic networks where frictional losses (as the result of fluid flow) must be minimized. Ball valves are configured with an orifice drilled through a cylinder (or sphere) in the valve stem such that no volume is displaced as the orifice within the stem is rotated to close the associated line. If it is desired to automate a laboratory soils test or a process involving a hydraulic network where frictional losses must be minimized, then ball valves controllable by computer or other logic networks are required.

It should be mentioned that solenoid valves, whose plungers are operated by a magnetic coil (solenoid), may be operated by computer signal. However, these valves are positive displacement valves and liable to cause all the problems discussed above. Additionally, solenoids produce intense magnetic fields which collapse to produce voltage spikes of considerable magnitude that feed back into electrical lines. Such voltage spikes can cause damage to sensitive electronic components.

Background

Systems to open and close ball valves have appeared in the market recently. The devices are electro-mechanical in nature and consist of several components, namely an air-operated, double-acting load pot, a rack and spur gear, a four-way solenoid valve, and a ball valve. Air pressure (controlled by a four-way solenoid valve) drives the load pot that displaces/moves the rack and turns the spur gear that is attached to the stem of the ball valve, allowing the valve to be opened or closed in response to directed air pressure pulses. Several disadvantages are evident in this system, notably, (a) large size, (b) high cost, (c) mechanical complexity, (d) the requirement for an air pressure supply for the solenoid valve, (e) pollution to the electronic environment caused by the operation of a solenoid (described above), and (f) the fact that present commercially available systems have no compatible electronics to allow communication or interface with logic networks.

Because these disadvantages make presently available commercial devices unacceptable for the desired system, a scheme for controlling ball valves was designed and the system fabricated. The resulting controllable valve is described below.

Description and Operation

The general schematic of the automated valve system is shown in Figure 5. The system consists of mechanical components and an electronic package that serves as an interface to allow communication with and control by a computer. The mechanical components and their operation and the logic of the controlling electronic package will be described separately below.

The mechanical components in the system include a small electric a-c motor that is mounted on a metal frame. The shaft of the motor is connected to the stem of the ball valve through an adapter that allows the motor shaft and valve stem to be clamped together with setscrews; this arrangement allows the valve to be turned by the motor. It should be mentioned here that it is unnecessary to reverse the direction of the motor; for the design that will be described, motor rotation occurs in one direction. *It is necessary* to sense conclusively whether the valve is open or closed. This is accomplished by electronic circuitry interacting with the mechanical system through (two) microswitches. A set of cam screws 180 deg apart are placed on the top of the rotating cam adapter shaft that contacts and actuates a microswitch called S1 in Figure 5. A second set of cam screws below, and perpendicular to the first set, acts on a microswitch called S2. Signals from the microswitches S1 and S2 are sensed by the electronic circuitry so as to identify the state of the valve (open or closed), and the circuitry allows logic commands from a controlling computer to operate the motor, opening or closing the valve (or many valves in parallel) using industry- standard high or low logic signals. It should also be noted that with this mechanical/electronic configuration, the software required for precise computer control is minimal. Emphasis has been placed on the fact that easy
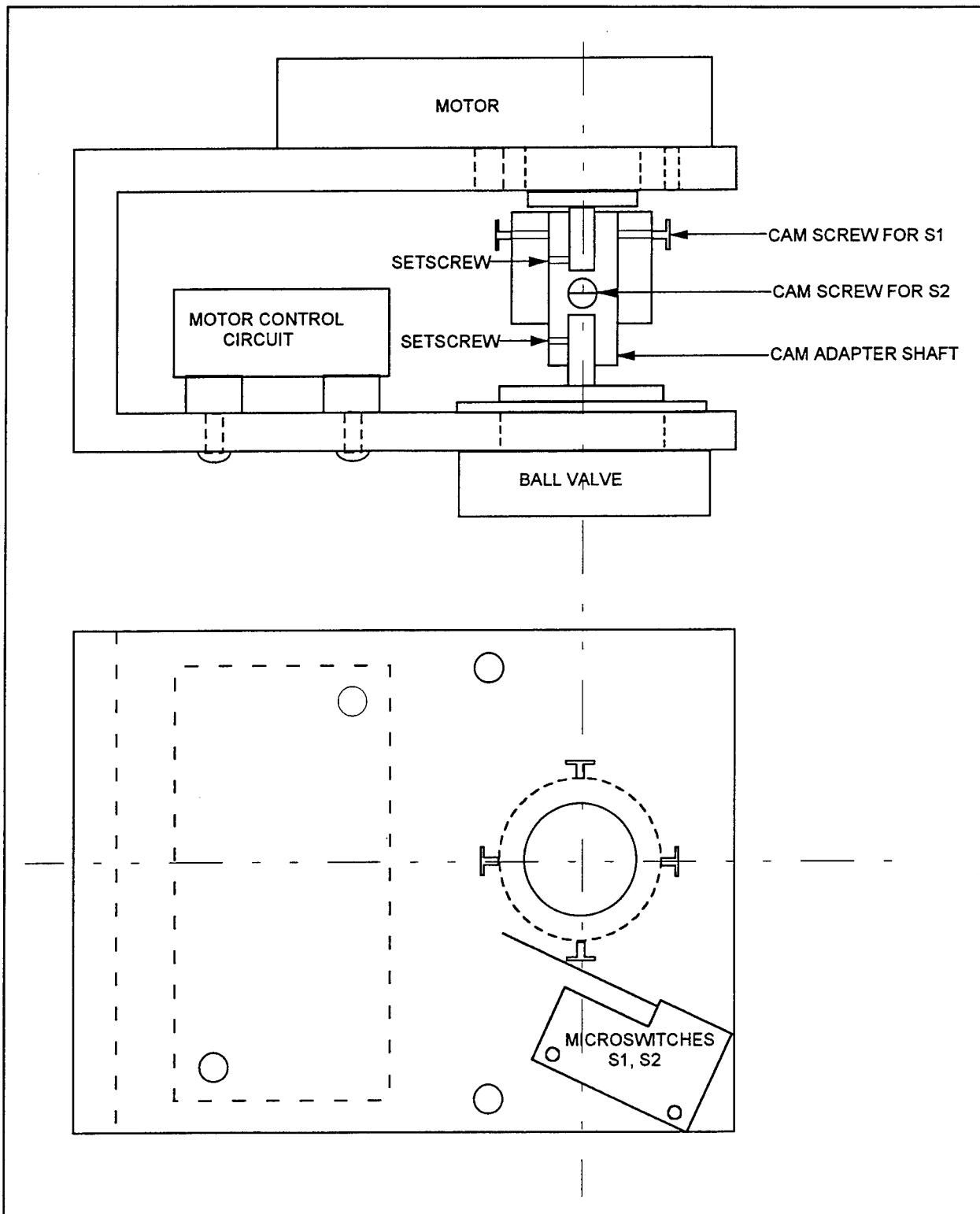
Figure 5.   Mechanical schematic of the automated valve

identification of the state of the valve is possible, and this is important in the event of a power failure in which the computer may lose data, and therefore the status of the position of the associated valve(s).

The electronic controller shown schematically in Figure 6 consists of the following components:

a. A quad 2-input NAND gate (7400/74LS series).

b. A light-emitting diode (LED).

c. A current limiting resistor (R1).

d. Two subminiature integral lever microswitches (S1, S2), also see Figure 6.

e. TTL/CMOS-compatible solid-state relay or optomos solid-state.

f. Switches (RY1, SW1).

g. A fuse (F1).

h. A motor-starting capacitor (C1).

i. a-c synchronous motor.

The 5-volt direct-current (VDC) power is supplied by an external power supply or computer digital output channel set to logic 1 (approximately 5 VDC) or an analog output channel set for 5 VDC. The synchronous motor requires 120 volts alternating current (VAC). The fuse (F1) provides protection for the motor and safety against shock hazard. The circuit, as shown, functions as a circuit using one inverter in conjunction with an OR gate, requiring two chips. Because a quad 2-input NAND gate is used along with three gates that serve as inverters (Inv 1, Inv 2, Inv 3) with the remaining gate as a NAND gate, only one integrated circuit (IC) chip is required. Input parameters are (1) logic 0 closes the valve and (2) logic 1 opens the valve. The input logic is applied by a computer or other logic network. The following description uses the NAND gate logic (Table 1) and the logic condition of the overall circuit.

Table 1 NAND Gate Truth Table		
A	B	X
0	0	1
1	0	1
0	1	1
1	1	0
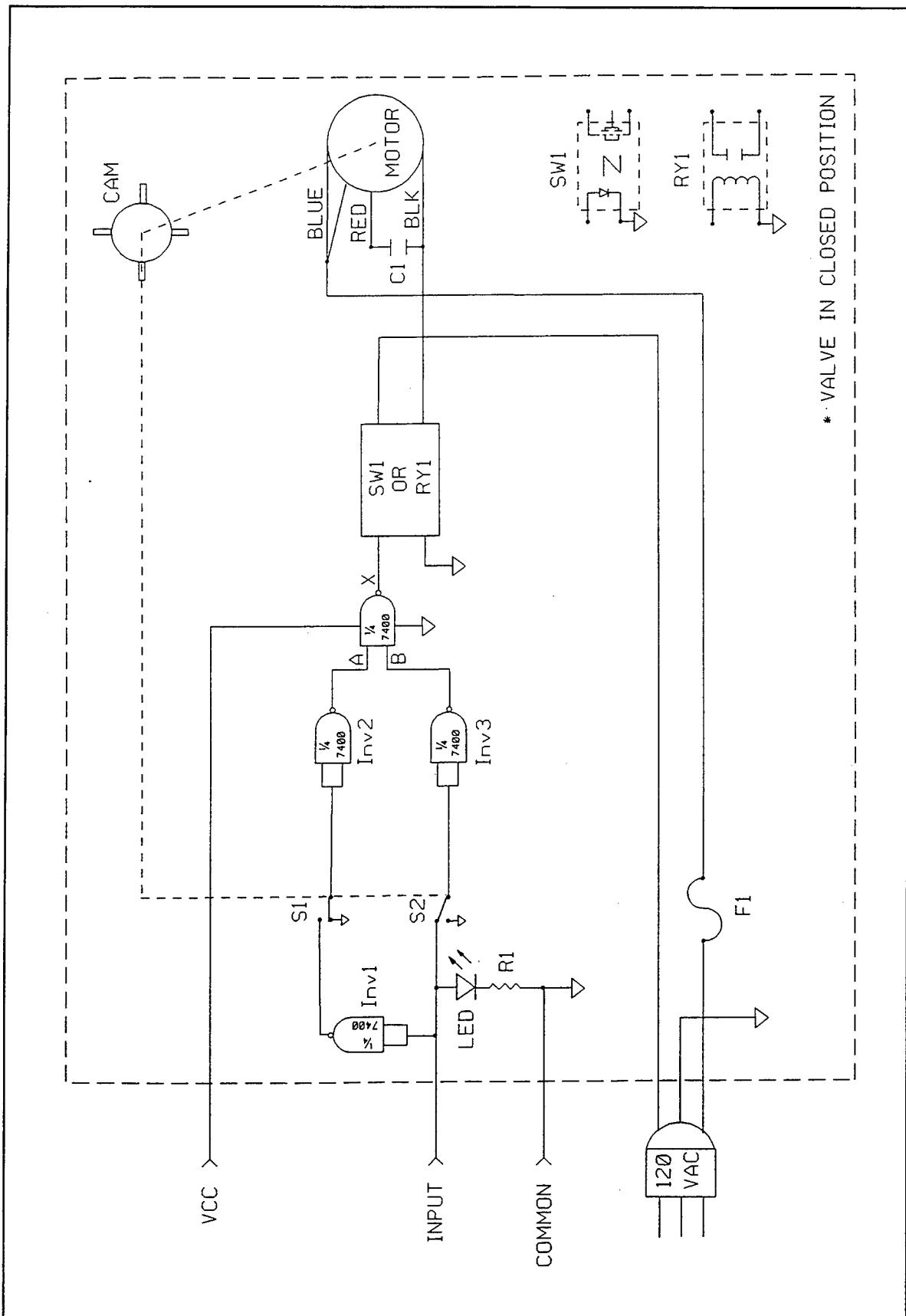
Figure 6.   Electrical schematic of the automated valve

Beginning with the valve in the closed position, a logic 0 exists at the input, the motor is stopped and a cam screw is in contact with the microswitch S1 that is pressed open. Microswitch S2 is not in contact with a cam screw and is in the normally closed position. The LED is "off" indicating logic 0 input, and the valve is closed. The Inv 1 output is a logic 1, but this is unimportant since S1 is open. With S1 open and Inv 2 input at ground potential, a logic 0 at both the Inv 2 and Inv 3 inputs, a logic 1 exists at both the Inv 2 and Inv 3 outputs. The NAND gate inputs A and B are both logic 1, thus the output X equals a logic 0 (see Table 1). No current flows to the solid state relay/solid state switches RY1 or SW1, so no voltage is applied to start the motor.

To open the valve, a logic 1 is applied to the input. The LED is now "on," the Inv 1 output goes to logic 0, and S1 opens. Inv 2 input is logic 0 and Inv 2 output is logic 1. Inv 3 input goes to logic 1 and Inv 3 output goes to logic 0. Now the NAND gate inputs A equals logic 1 and B equals logic 0 changing the output X to a logic 1 (see Table 1). The current now flows through RY1/SW1 closing the contact to supply voltage to start the motor. As the motor rotates, the cam screw leaves S1 releasing the microswitch to the normally closed position. Since the Inv 1 output is logic, the state of the circuit remains the same as the motor continues to turn until a cam screw contacts microswitch S2. S2 is now open, applying a logic 0 to the Inv 3 input. Since logic 0 is still present at the Inv 2 input, A and B are logic 1, X is logic 0, and the motor is stopped with the valve in the open position. The LED remains "on" indicating that the valve is open.

To close the valve, a logic 0 is applied to the input. The LED goes "off." The Inv 1 output goes to a logic 1, S1 closes, Inv 2 input is a logic 1 and Inv 2 output is a logic 0. The Inv 3 input is a logic 0 so Inv 3 output is a logic 1. NAND gate input A is logic 0, input B is logic 1; therefore, X becomes logic 1. Current flows through RY1/SW1 closing the contact to supply voltage to start the motor. As the motor rotates, the cam screw leaves S2 releasing the microswitch to the normally closed position. Since the input is already logic 0, the circuit remains the same, and the motor continues to turn until a cam screw contacts microswitch S1. Microswitch S1 is now open, applying a logic 0 to the Inv 2 input. Since the Inv 2 and Inv 3 input is a logic 0, A and B both become a logic 1, and X becomes a logic 0. With X a logic 0, the motor stops with the valve in the closed position.

Advantages and New Features

Advantages of the logic-controlled valve constructed for the present investigation are as follows:

a. Valves may be controlled with simple software and short routines that permit fast computer operation.

b. Simultaneous operation and control of many valves is not only possible, but also made simple by electronic circuitry controlling the valves.

c. Valve state (open/closed) is easily identified and recognized by a computer (or other logic system).

d. Precision valve positioning is possible with the system.

e. The system is much less expensive than those presently on the market to perform the same work.

f. The system offers small size over presently available commercial products.

g. The system is mechanically simpler and easier to use than presently available commercial products.

h. The system offers control by computer or other logic device.

i. The system operates without solenoid valves; therefore, substantially less electronic pollution results.

j. Remote applications are possible with the system described and are simpler than with presently known available hardware.

k. The design described is easily extended to other configurations (three-way valves, four-way valves, throttling systems, for example).

l. The design is based on proven technology (of individual components), suggesting high reliability.

m. The electronic control circuitry developed for use with the system is compatible with standard TTL and CMOS technology.

It was necessary to construct a controllable valve for the work at hand because commercially available products were unacceptable. Because the automated valve system constructed for the work of this research was unique, it was disclosed for patent in May of 1991; patent number 5,178,361 was granted for this system by the U.S. Patent Office in January 1993.

5 Testing Procedure Executed by Software

The number of steps and procedures involved in a chamber test depend on the environmental conditions needed to be simulated and the soil parameters desired to be measured. For example, a soil specimen may be subjected to any combination of procedures to (1) ensure air removal and water saturation, (2) allow consolidation under a hydrostatic pressure, (3) force water flow through the specimen to determine (coefficient of) permeability, or (4) apply axial loading to determine stiffness or strength. Software prepared to control the testing procedure consists of subroutines that are called from a main program. With little difficulty, a main routine can be assembled to perform a special or unique test using subroutines in the proper sequence. Consolidation tests in which the ratio of axial to lateral stress is not unity are occasionally required. For that reason, a subroutine to perform this function has been prepared and may be called when needed. The subroutines and their operation will be described here. The subroutines are SETUP, SATURATION, CONSOLIDATION, and SHEAR. Each subroutine and the operations and functions performed by it will be described separately.

SETUP

During SETUP, the technician installs the prepared specimen on the base, encloses it in a (rubber) membrane, measures its height and diameter, then assembles the chamber around it in preparation for subsequent stages where the process is under computer control. SETUP is the only manual operation in the procedure.

One of the major objectives of SETUP is to prepare the specimen so that it can be saturated quickly and easily; SETUP is actually the (manual) beginning of the saturation phase. Certainly if the test is to be conducted on an unsaturated specimen, then a less stringent SETUP procedure may be adopted. To prepare for SETUP, the stones in the cap and base must be oven-dry and free of soil that could restrict water flow during the ensuing steps and impair the entire process. All operations in the procedure rely on unrestricted water flow into and out of the soil specimen. It is important that the attending technician determine and ensure that the porous stones are clean, free draining, and initially dry. The stones should be dry because surface tension associated with

air/water interfaces trapped in the interior of the stone may completely block off some areas through which liquid and gas flow could otherwise occur and restrict flow through other areas. As a result, the permeability of the stones will decrease, reducing the overall efficiency of the process.

Additionally, stones that contain water will limit the level of vacuum possible because of the vapor pressure associated with water (which is a function of temperature). The amount of air/gas removed from the voids of a soil is directly proportional to the level of vacuum that is applied. If a high level of vacuum is not possible because of water in the system (resulting in high water vapor pressure), then greater quantities of air will remain in the system after deairing, increasing the difficulty of achieving acceptable levels of soil saturation.

Technicians should wash and purge stones in the caps and bases of the chamber equipment with distilled water after each test (before placing the stones in an oven to dry) to remove salts, chemicals, and soil particles that, if allowed to build up, will contaminate future samples and eventually ruin the stones by clogging the pores. To prevent water entering the stones from the plumbing system during SETUP, water in the lines should be blown out and the (piping) system purged with pressurized air to thoroughly dry (the piping system) before SETUP is begun.

After the chamber is assembled around the specimen, the chamber is filled with fluid and a chamber pressure burette connected to the chamber (as shown in Figure 7) so that pressure may be applied to the chamber through an air/water interface. Valve V7 is closed and valve V10 opened and a small amount of pressure (for example 1 psi) is applied to the chamber pressure burette by an external source to ensure a positive pressure on the test specimen. The pressure control source applied to valve V10 should be a pressure/vacuum source because it will be necessary to apply vacuum through the chamber pressure burette. Air diffusion through the chamber fluid and membrane (and into the soil specimen) may cause problems in long-term tests. However, air/gas diffusion may be stopped with a mercury trap where air pressure is applied through a column of mercury. A mercury trap will, for all intents and purposes, stop air diffusion. However, the use of a mercury trap may cause problems with differential pressure changes over time as water level fluctuates because mercury is 13.6 times as dense as water. Additionally, mercury is potentially hazardous and toxic to personnel, and exposure to mercury may contaminate and damage certain types of equipment (such as copper tubes and brass fittings); therefore, human safety and equipment integrity become important issues whenever mercury is used.

During initialization (see Figure 7), the computer opens valves V2, V3, V5, and V6 while closing valves V1 and V4. The technician (manually) closes three-way valve V8 and valve V9 to the voltage-to-pressure transducers and balance chamber, respectively. At this point, an external pressure/vacuum regulation system is connected to the burette on valve V5 and a vacuum level of 1 or 2 psi (say an amount, D_m) is applied to the specimen, transducers 1 and 2, and the piping system enclosed between valves V1 and V4 as can be seen in Figure 7.
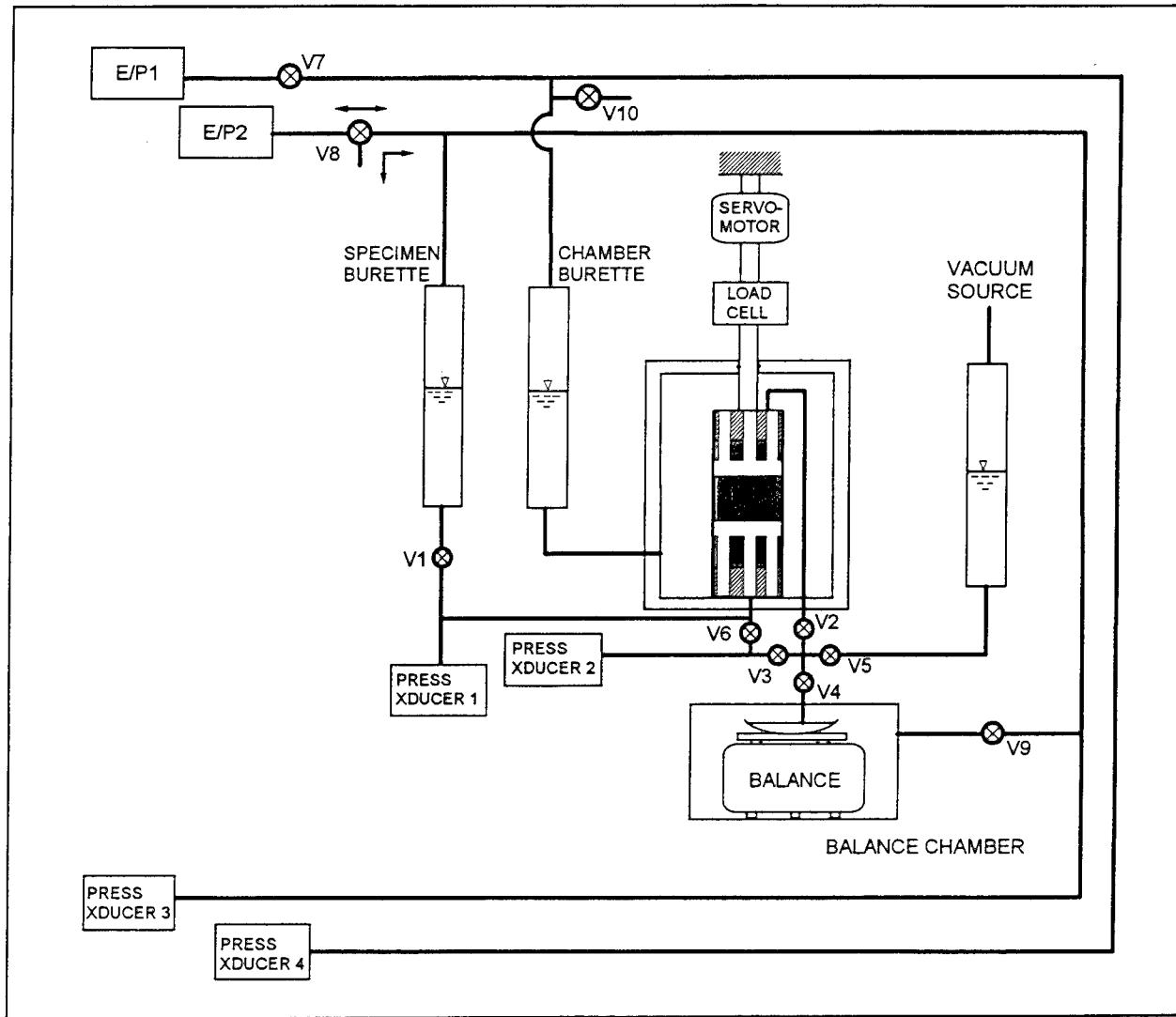
Figure 7.   Piping system of computer-automated test configuration

At this point, one of two procedures may be used, depending on the final consolidation pressure to be applied. If the final consolidation pressure to be applied is more than 13 to 15 psi, then the level of vacuum in the enclosed volume that includes the soil specimen may be increased with the external pressure control system to the maximum that the equipment can achieve (the level applied should ideally be greater than 14 psi). If the soil under test is clay, maximum vacuum should not be allowed to remain on the system for more than 10 min because high levels of vacuum will desiccate plastic clays causing irreversible specimen damage. If the soil is clean sand or of low plasticity, then high vacuum may be applied for relatively extended periods with little, if any, damage. If the final effective consolidation pressure is to be less than 13 to 15 psi, then a differential vacuum procedure should be used to remove as much air as possible to facilitate saturation, but without application of high levels of vacuum that will overstress and damage the specimen.

If a differential vacuum procedure is used, some operator skill will be required, in that a second pressure control system must be connected to the three-way valve V10 (which at this time is closed to the transducer, E/P1, and open to the chamber burette). Vacuum is applied to the chamber with simultaneous vacuum applied to the specimen through the burette attached to valve V5. The differential vacuum procedure is so named because during its execution, vacuum levels in the specimen and in the chamber are increased simultaneously maintaining a differential, D_m, between the two zones. Vacuum level in the specimen is greater by the amount D_m, and the two levels are increased until the vacuum applied to the specimen is the maximum that the equipment in use can achieve. As in the previous procedure, maximum vacuum must not be applied more than 10 min to a clay soil of high plasticity. At this time, valve V5 is closed (by manual command from the computer keyboard); vacuum source from V5 is disconnected and reconnected to the three-way valve V8 (that is in the closed position). Valve V8 is now (manually) turned to the position to apply vacuum from the source to the burette that is connected to valve V1. Maximum possible vacuum is now applied to the specimen burette, valve V1 is manually opened using the computer and the vacuum is applied to the specimen and transducers through the specimen burette (see Figure 1). Vacuum levels in the chamber and in the specimen (and associated lines) are simultaneously reduced until vacuum level in the specimen has been reduced to atmospheric pressure. At this time, pressure level in the chamber should be at $+D_m$. Valve V6 is closed (manually from the computer), $+D_m$ is set on transducer E/P1 (using the computer), and E/P2 is set to atmospheric pressure. Transducers E/P1 and E/P2 are (manually) connected to their respective lines by manually opening valve V7, setting valve V8 to transducer E/P1, and closing valve V10.

The system is now set to begin automated back pressure saturation.

Back Pressure Saturation

Back pressure saturation is a procedure in which pressures inside and around a soil specimen are increased simultaneously to compress any gas that is present in the soil. Compressing the gas reduces its volume; consequently, water entering the specimen to occupy volume left by shrinking gas bubbles increases the (water) saturation of that specimen. Additionally, compressing a gas (volume) with hydrostatic pressure stiffens it inside the specimen and makes it less compressible; this is a desirable alternative if the gas cannot be completely removed. However, removal of gas by back pressure is further facilitated by the fact that solubility of gas in water increases as pressure increases,[1] so that a greater volume of gas dissolves in pore water at elevated (back) pressure and is, for all intents and purposes, removed. The gas is still present, but its effect on system compressibility is eliminated since it is

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[1] Henry's law of solubility states that the mass of a slightly soluble gas that dissolves in a definite mass of a liquid at a given temperature is very nearly directly proportional to the partial pressure of that gas. This law holds for gasses that do not chemically unite with the solvent.

dissolved in water, and can be flushed from the specimen if the soil is sufficiently permeable.

Back pressure saturation effectively began in the manual SETUP operation (described above) in which vacuum levels are applied simultaneously to the chamber and the specimen pore space. Vacuum applied in the manner described causes gas present in the interstices of the soil specimen to expand, migrate to the surface, and be removed from the soil. After the application of vacuum, (positive) back pressure is applied to ensure and enforce an even higher degree of saturation. Because pressures are applied simultaneously to the interior and exterior of the soil specimen and the pressure differential[1] (across the membrane) is not allowed to exceed a specified limit, the automated procedure ensures to the maximum possible extent that the skeleton of the soil specimen is not stressed by a pressure larger than the specified differential.

Automated back pressure saturation begins with the computer closing valves V4, V5, and V6 and opening V1, V2, and V3. The computer then begins sending voltage signals to transducers E/P1 and E/P2 to simultaneously increase pressure in the specimen and the chamber. The pressure increases at a rate, R, psi/min (the default value of R is 1 psi/min if a value is not specified). The differential, D_m, is maintained between the chamber and the specimen at all times. Monotonically increasing pressure compresses gas inside the soil, and water flows into the specimen.

The pressure gradient that develops over the height of the specimen is also a measure of damage to the specimen that occurs as a result of back pressure application. Pressure developing at the bottom of the specimen is measured on pressure transducer 2; pressure developing at the top is measured on pressure transducer 1. Back pressure application invariably results in a pressure gradient over the length of a specimen and some structural damage to the specimen. For the sake of achieving saturation in a time efficient manner, some pressure gradient resulting from back pressure application must be tolerated. However because the process is under computer control, potential damage as the result of back pressure application can be monitored, managed, and minimized. A value called *DIFFMAX* (which is the same as D_m discussed above) is specified during initialization; this is the parameter that controls the amount of damage that the specimen will be subjected to during saturation. *DIFFMAX* is the value of pressure gradient over the length of the specimen that must never be exceeded during conduct of the test. In equation form, it is

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[1] A differential develops because of a lag that occurs between the time a pressure or vacuum is applied to the surface of a closed soil specimen and the time that the pressure or vacuum becomes uniformly distributed through the pore space of that specimen. The time lag is related to pore size and surface tension of water. In sands with relatively large pore sizes, pressures in the voids that result from surface tension are relatively small. Therefore, pore pressure equilibrium is reached quickly since the passages through which flow of water and gas must occur are large and the pressures that may block off internal zones of the specimen relatively small. Conversely, in clay specimens with small pore spaces, pressures produced by surface tension are large and the flow passages small. Therefore, a greater amount of time is required for pore pressure equilibrium in fine-grained soils. Additionally, fine-grained soils are more-susceptibile to irreversible structural damage as the result of pressure application.

$$DIFFMAX \leq (T1 - T2) \tag{12}$$

where

$T1$ = pressure sensed by transducer at the top of the specimen

$T2$ = pressure sensed by transducer at the bottom of the specimen

To avoid exceeding the specified value of *DIFFMAX*, the back pressure saturation subroutine is trapped such that if the value of ($T1 - T2$) becomes equal to *DIFFMAX*, application of back pressure is arrested until the value of ($T1 - T2$) decays/decreases to *DIFFMAX/2*. At that time, back pressure application will resume at the rate, R. Obviously, if *DIFFMAX* is set equal to zero, then whenever the system attempts to apply back pressure, the trap will arrest the process and back pressure application will never begin; if *DIFFMAX* is set to a small value, then back pressure application will proceed very slowly. A compromise between acceptable damage to the specimen and reasonable time required for achieving saturation must be made. Generally, guidance is to limit *DIFFMAX* to an appropriately small fraction of the final effective confining pressure, σ_c.

For the sake of the safety of personnel and equipment, it is desirable to keep the level of back pressure as small as possible to achieve acceptable soil saturation. Therefore, checks for saturation are made often as back pressure is increased; back pressure application will be terminated immediately when the minimum required value of saturation is achieved. For example, specimen saturation is measured in terms of Skempton's B-parameter to be described in detail below. The parameter will be checked after each 5-psi increment of back pressure by calling a subroutine called BPARAM. The subroutine returns to the main control routine to apply additional back pressure if the condition for soil saturation is not satisfied. If the saturation requirement is satisfied, the main control routine continues to the next stage, which is consolidation.

B-Parameter Check

Definition of B-parameter

Saturation of a soil specimen in a chamber test is checked and expressed in terms of Skempton's B-parameter; this parameter is determined by increasing the chamber pressure with no specimen drainage allowed, and observing change in fluid pressure within the specimen. B is defined as

$$B = \frac{\Delta u}{\Delta \sigma_3} \tag{13}$$

where

Δu = change in specimen pore water pressure under undrained conditions in response to increment of hydrostatic pressure

$\Delta\sigma_3$ = increment of hydrostatic pressure applied to the specimen inside the chamber

B-parameter may be expressed in terms of material properties as

$$B = \frac{1}{1 + n\left(\dfrac{C_w}{C_c}\right)} \tag{14}$$

where

n = soil porosity

C_w = compressibility of air/water mixture in the soil voids

C_c = compressibility of the soil skeleton

When air is present in the voids along with water, C_w is greater than the compressibility of water. It should be noted that the value of C_w is equal to the compressibility of water only if the specimen is completely saturated. Similarly, if the specimen voids are completely filled with air, C_w becomes equal to the compressibility of air.

The limiting value of the B-parameter is unity as complete saturation is approached; however, measured values should, theoretically, always be less than unity because the ratio C_w/C_c is never exactly zero. That is, even though the compressibility of water is (usually) small compared to that of the soil skeleton, the ratio C_w/C_c has some finite value that result in a measured B-parameter smaller than unity. As a result, perfect transfer of hydrostatic pressure to the specimen pore water through the membrane does not occur. If a soil specimen is completely compliant (i.e., $C_c >> C_w$) and is water saturated, then hydrostatic pressure applied to that undrained specimen is transferred undiminished to the pore water and the B-parameter is determined to be unity using Equation 14 (Bishop and Henkel 1962). However, in reality, if there is air/gas present in the soil voids and the specimen possesses some stiffness (i.e., has resistance to hydrostatic compression), then hydrostatic pressure applied to the specimen will result in pore pressure response that may be considerably less than unity.

Because of the high compressibility of gas, as hydrostatic pressure is applied through the membrane, the gas will compress and some of the pressure will be applied to the soil skeleton; the remainder of the pressure will be applied to the specimen pore air/water system. Therefore, the B-parameter determined by Equation 14 will be less than unity and, depending on the amount of pressure carried by the soil skeleton, the soil could be overstressed

and damaged during a check for saturation. Overstressing a soil specimen during saturation check is obviously undesirable; the procedure for managing this situation with programmed control will be discussed later. The minimum B-parameter that the equipment under design is programmed to attain is 0.95, although it must be noted that at this value of B-parameter, water saturation is very nearly 100 percent.

It should be stated that special provisions need not be made for soils of normal stiffness, such as undisturbed and/or compacted soils that are normally to moderately overconsolidated. However, in the case of stiff and highly overconsolidated clays and clay shales as well as highly cemented sands and rocks, soil stiffness may be so great that measured values of Skempton's B-parameter in highly saturated soils will never reach, or even approach 0.95. For such (extremely stiff) materials, the correct procedure is to check values of the parameter at several, successively higher increments of applied chamber pressure. If the B-parameter is constant when measured under successively higher increments (which means that the term, $n*C_w/C_c$, has a constant value that is significant when compared to zero), then saturation may be assumed even though the value of the parameter is less than 0.95. The B-parameter measurement procedure incorporated into the software for standard use is intended for soils of normal stiffness. No provision in the standard software is made for stiff or highly cemented soils; however, if there is the need for such capability, then the controlling software may be readily modified to accommodate the proper procedures for such materials.

Possible damage during B-parameter check

The procedure for computer-controlled and applied back pressure checks the B-parameter after the application of each 5 psi of back pressure. The increment of (hydrostatic) pressure used to determine the B-parameter is also 5 psi. In nearly saturated soils, applied hydrostatic pressure is transferred almost entirely to the pore water with little of the pressure being taken by the soil skeleton. Conversely, in specimens of low saturation, significant pressure may be applied to the soil specimen during a B-parameter check to the extent that the soil may be overstressed and damaged. The amount of pressure transferred to the soil skeleton may be expressed as

$$D = \Delta\sigma_3 - \Delta u \tag{15}$$

where

D = pressure applied to the soil skeleton

The maximum pressure applied to the soil specimen during application of back pressure for saturation may be controlled by limiting the quantity D. This is, in fact, how the software prevents overstressing the specimen during B-parameter check. The quantities $\Delta\sigma_3$ and Δu are monitored during hydrostatic pressure application and the software is trapped to limit the difference, D, to $DIFFMAX$ as defined above, that is,

$$\Delta\sigma_3 - \Delta u \le DIFFMAX \qquad\qquad (16)$$

If during B-parameter check, the quantity D becomes equal to $DIFFMAX$, then pressure application is arrested at that point, the chamber pressure is decreased to its value at the beginning of the B-parameter check and the process of back pressure application continued. Operating in this manner ensures that the specimen is never subjected to an (effective) pressure greater than $DIFFMAX$ during saturation.

Software-controlled B-parameter procedure

A B-parameter check is performed by the subroutine *bparam* that is called from the subroutine *SATURATION*. The sequences used by *bparam* are as follows:

a. Valves V1, V2, and V3 are closed by the computer.

b. The current values measured by the chamber pressure (see Figure 7) transducer 4 and the pressures at the top (transducer 2) and bottom (transducer 1) of the specimen are acquired and stored.

c. With the intention of ultimately increasing 5 psi, the automated system begins increasing the chamber pressure using the voltage-to-pressure transducer, E/P1.

d. If the difference between the change in chamber pressure and the change in induced pore pressure becomes equal to DIFFMAX (the condition described by Equation 16) before the hydrostatic pressure in the chamber can be increased by 5 psi, hydrostatic pressure application is stopped, the chamber pressure is returned to its level at the beginning of the B-parameter check, valves V1, V2, and V3 are opened, the system is allowed to rest for 15 sec, then back pressure application is resumed.

e. If it is possible to apply a hydrostatic pressure increment of 5 psi without violating the condition expressed in Equation 16, then the value of the B-parameter is computed according to Equation 13.

f. If the value of the B-parameter is less than 0.95, then the chamber pressure is decreased to its level at the beginning of the B-parameter check; valves V1, V2, and V3 are opened; the system is allowed to rest for 15 sec, and back pressure application is resumed.

g. If the value of the B-parameter is greater than or equal to 0.95, then the chamber pressure is held at this level for a period of 5 min. If the B-parameter remains at a value greater than or equal to 0.95 at the end of 5 min, then the saturation check is satisfied and the system continues to the next stage of testing, i.e., consolidation.

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h. If at the end of the 5-min period in step 7 above, the value of the B-parameter is determined to be less than 0.95, then the chamber pressure is decreased to its value at the beginning of the B-parameter check, valves V1, V2, and V3 are opened, and back pressure application is resumed.

Consolidation

Primary consolidation and secondary compression

Consolidation is the term used to describe compression of a soil by externally applied pressure. When referring to a soil specimen in a laboratory test, consolidation generally consists of two phases: primary consolidation and secondary compression. Primary consolidation is the phase of interest in the process controlled by the computer-automated equipment under development; it consists of liquid and/or gas being squeezed out of the soil specimen through continuous voids by applied pressure. Secondary compression is the result of continued volume change and readjustment of the soil skeleton in response to hydrostatic pressure after the completion of primary consolidation. However, volume change during secondary compression occurs so slowly that no excess pore pressure develops as a result. Secondary compression increases at a decreasing rate with time, but continues indefinitely; its exact nature is not completely understood; however, some generalizations may be made concerning soils most likely to exhibit large amounts of secondary compression.

Sowers and Sowers (1970) suggest that low to moderately compressible inorganic soils seldom exhibit significant secondary compression; however, it may be the major part of the total compression of highly organic or micaceous soils. The rate of secondary compression generally increases with increasing soil plasticity and varies inversely with the degree of overconsolidation. The amount of secondary compression is decreased by remolding. Since soil specimens continue to decrease in volume for extended periods as the result of secondary compression, and since consolidation is considered to be complete at the end of primary consolidation, for the design of a practical algorithm to control a laboratory test, it will be necessary to define conditions to separate primary consolidation from secondary compression.

When a saturated soil specimen is subjected to a hydrostatic pressure increase, the pressure is initially carried by the water in the pores of the soil. The pressure increase that occurs in the pore water is referred to as hydrostatic excess pore water pressure. Primary consolidation is the process where hydrostatic excess pore water pressure is transferred from the pore water to the soil skeleton as water is squeezed out of the voids. The amount of water squeezed out of the soil depends on the pressure increment, soil compressibility, and volume of the specimen. The rate at which water is squeezed out depends on the permeability of the soil under test and the geometric drainage configuration of the test specimen.

The time required for consolidation is a function of the (coefficient of) permeability and the longest drainage path within the specimen; specifically, the

time for a given degree of consolidation varies as the square of the longest drainage path within the soil specimen. To minimize the time for consolidation, the length of the longest path to drainage within the soil specimen must be minimized. The minimum length of drainage path in the circular cylindrical triaxial test specimen under consideration is the radius of the specimen. If the soil under test is sand or a similar coarse granular material, the minimum drainage path is probably unimportant because the (coefficient of) permeability of the soil is so large that the time for complete consolidation is short.

However, in the case of plastic clay soils, the (coefficient of) permeability may be so small that extended periods of time are required for complete primary consolidation. For example, if the height-to-diameter ratio of the specimen is 2.5, then time for complete consolidation is 25 times longer if the drainage path within the specimen is the height as opposed to the radius.

In the case of clay specimens, time for consolidation (as well as saturation) may be minimized by enclosing the specimen in a "filter cage" consisting of strips of permeable filter paper placed around the circumference of the specimen and extending axially down the length of the specimen. The configuration of the filter cage is shown in Figure 8. As shown in Figure 8, the filter cages must overlap the specimen top cap and base platen to be in full communication with the drainage paths at the top and bottom of the specimen. The filter cages must be separated by a distance of one specimen radius to be most effective. It is required that the filter paper from which the cage is constructed have much greater permeability than the plastic clay soil that is drained. In addition to facilitating the movement of gas and water into and through the soil, another function of the filter cage is to facilitate pore water pressure equalization (in plastic clays of low permeability) during shear.

Water expelled from the specimen during consolidation collects in the pan of the water mass measurement balance shown in Figure 7; this volume is determined as described in Chapter 2 by operating on the indicated mass. The automated system monitors the consolidation process and determines when it is finished using the algorithm described below. The advantage of progressing to the next stage of the test directly after consolidation is that the soil under test is not subjected to an arbitrary amount of secondary compression that occurs between the time that primary consolidation is finished and the time that the next stage of the chamber test begins. The control system is able to precisely detect the end of primary consolidation and proceed immediately to the next stage so that idle time after primary consolidation is eliminated. The rationale for the algorithm developed and used is described below.

Software-controlled consolidation procedure

After the specimen has been subjected to the B-parameter test and the value computed to be greater than or equal to 0.95, the subroutine CONSOLIDATION is called. At this point in the procedure, pressure in the chamber is equal to that at the end of the last B-parameter check and valves V1, V2, V3,
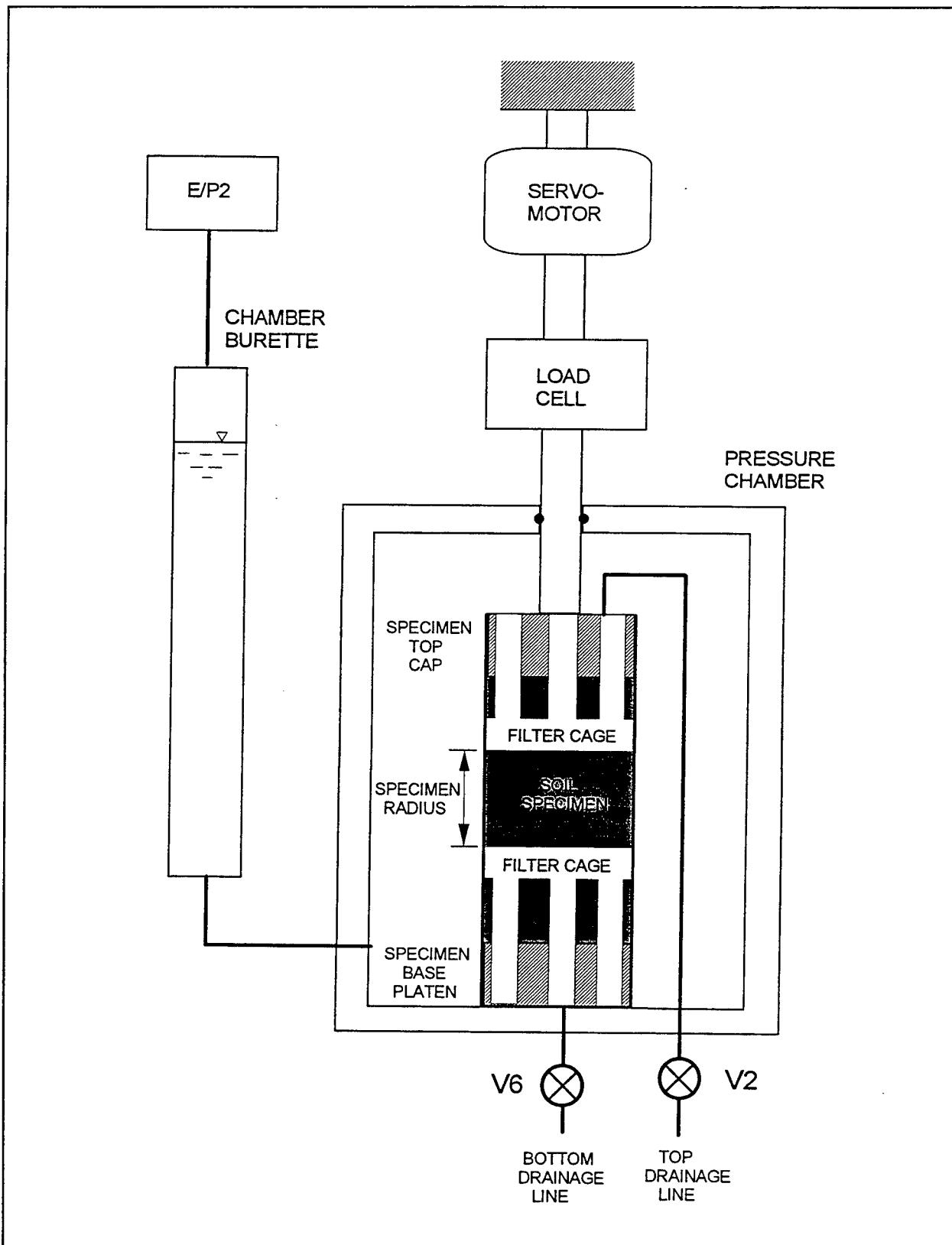
Figure 8.   Schematic of pressure chamber and soil specimen

V4, V5, and V6 are all closed. The sequence used to control the process of consolidation from this point is as follows.

   a. Valves V2, V3, and V6 are opened.

   b. The current chamber pressure is increased by an amount such that the resulting difference between the chamber pressure and the back pressure after the increase will be SIGCON, the desired effective consolidation pressure that is read as input during initialization.

   c. Valve V4 is opened to allow water drainage from the specimen. The system begins counting time when valve V4 is opened and mass readings are acquired at the time intervals t = 0.25, 0.5, 1, 2, 4, 8, 15, 30, 60, 120, 240, 480, and 1,440 min.

   d. After 30 min, and each 30-min increment thereafter, valve V6 is closed, and the pressure increase as measured by transducer 2 (Figure 7) at the bottom of the specimen is observed. If consolidation is complete, the reading indicated by transducer 2 will remain constant; otherwise the reading will increase with time. If the pressure indicated by transducer 2 is greater than or equal to SIGCON/20 or 0.4 psi over a 2 min interval, then valve V6 is reopened and drainage allowed for an additional 30-min period at which time V6 will again be closed and pressure rise will be checked. When the pressure rise over a 2-min interval is determined to be less than 0.4 psi, then primary consolidation is complete. At this point, a final mass reading and time are acquired, and the controlling software continues to the next phase of the test which is shear strength determination.

Shear Strength Determination

Background

The final phase of the general chamber test is that in which axial loading is applied to the soil specimen to fail it and allow determination of its shear resistance. In triaxial tests, drainage conditions may be controlled to perform unconsolidated undrained tests (UU tests), consolidated undrained tests (CU tests), and consolidated drained tests (CD tests) to simulate various construction-time sequences and scenarios. Using software control, hybrids of the normal triaxial tests or custom tests may also be performed. Any test in which the loading and/or drainage conditions can be described accurately can be performed by the present system.

By definition, the UU test is performed without allowing consolidation or drainage, and is the simplest to perform of the three basic triaxial tests in terms of the number of operations required for execution. Back pressure saturation may or may not be carried out in specimens on which CD tests are performed; if neither accurate consolidation-time data nor volume change data during loading are required (during CD loading), then back pressure saturation is

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unnecessary. The equipment under development is, in fact, most appropriate for conducting variations of the CU test or the CD test in which volume change data are required. Additionally, a procedure is developed for measuring volume change in unsaturated specimens during shear by measuring pressure in the pore air.

Equations that are used in the software for the *controlled strain test* as well as the *controlled stress test* are developed and shown. Simplifying assumptions made in the development are given and the implications discussed.

Controlled strain test

During a controlled strain test, a constant rate of axial deformation is imposed on the specimen while the resistance that develops in response to applied deformation is measured. For computation of (average) axial stress, the assumption is made that the specimen experiences a uniform cylindrical bulge in the radial/lateral direction as the result of deformation applied in the axial direction. Average axial strain is computed from measured axial deformation. The equations for average axial strain (ϵ_a) and average axial (deviator) stress (σ_a) are

$$\epsilon_a = \frac{\Delta l}{l_o} \tag{17}$$

$$\sigma_a = \frac{F_a}{A_t} \tag{18}$$

where

ϵ_a = average axial strain

Δl = measured axial deformation from start of shear

l_o = length of specimen in axial direction at the start of shear

σ_a = average axial stress (deviator stress)

F_a = effective axial force

    = total force (force transducer reading) - F_u

A_t = area corrected for axial deformation

$$A_t = \frac{\left(A_o - \frac{\Delta V}{l_o}\right)}{\left(1 - \epsilon_a\right)} \tag{19}$$

where

A_o = specimen cross-sectional area at start of shear

ΔV = volume expelled during shear

Another form of Equation 19 that could prove to be useful is

$$A_t = \frac{\left(V_o - \Delta V\right)}{\left(l_o - \Delta l\right)}$$ (20)

If a test is performed undrained, then obviously no volume will be expelled and ΔV is zero; however, the expression is presented in its general form and the term to account for specimen volume change during shear is included for completeness.

The rate of axial deformation applied to the specimen should be such that pore pressure equalization exists throughout the specimen at failure (maximum deviator stress). The procedure recommended by the American Society for Testing and Materials (ASTM) in Designation D-4767 (ASTM 1992) is to assume failure (maximum deviator stress) occurs after 4 percent axial strain. The recommendation of ASTM D-4767 is that rate of deformation be such that 4 percent axial strain is applied in an interval that is ten times the period required for 50 percent consolidation (t_{50}), which may be determined from data acquired during the consolidation phase of the test. The recommended rate of deformation is determined to be

$$\dot{\varepsilon} = \frac{\left(0.04 l_o\right)}{10 t_{50}}$$ (21)

where

$\dot{\varepsilon}$ = rate of axial deformation

t_{50} = time for 50 percent consolidation

In determining the time, t_{50}, from a consolidation curve, a correction must be applied (to the curve) to obtain the point of initial primary consolidation. The initial shape of the curve may be approximated as a parabola and the corrected initial point obtained by selecting two points at the beginning of the curve such that the ratio of the corresponding times is 1/4. For this purpose, choose points at times of 4 min and 16 min. Since the curve shape is (assumed to be) a parabola, the corrected initial volume reading, V_s, is then located a distance $(V_{16\,min} - V_{4\,min})$ above the volume expelled at 4 min, $V_{4\,min}$. The volume representing 100 percent consolidation is the volume observed at the end of the consolidation procedure, V_e. Fifty percent consolidation then lies halfway between the volumes V_s and V_e. That is,

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$$V_{50} = \frac{V_e - V_s}{2} \tag{22}$$

The procedure now consists of determining volume readings V_{t1} and V_{t2} observed during consolidation such that $V_{t1} \leq V_{50} \leq V_{t2}$; since the volume/time data are observed during consolidation and stored on disk, this task is readily accomplished through software. Parameters of a line on a semilogarithmic plot between data points (t_1, V_{t1}) and (t_2, V_{t2}) are determined. The slope and intercept of the line (m and b, respectively) are,

$$m = \frac{\left(V_{t_1} - V_{t_2} \right)}{\log \left(t_1 \right) - \log \left(t_2 \right)} \tag{23}$$

$$b = V_{t_1} - m \log \left(t_1 \right) \tag{24}$$

and t_{50} is determined from the expression

$$t_{50} = 10^{\left[\frac{V_{50} - b}{m} \right]} \tag{25}$$

Controlled stress test

In a controlled stress test, axial force applied to a circular cylindrical soil specimen is increased at a constant rate. An expression that gives the axial force to be applied as a function of time is

$$F_t = \dot{\sigma}_a \, t \, A_t + F_u \tag{26}$$

where

F_t = force applied by force control system

$\dot{\sigma}_a$ = desired rate of (axial) stress applied to specimen

t = time since the start of stress application

A_t = area corrected for axial deformation defined above

F_u = uplift

Equation 26 takes uplift into proper account as well as specimen area change due to lateral expansions from axial deformation according to Equation 20.

Code Execution

The source code to perform triaxial compression tests by computer control is given in Appendix A. The code is prepared in the BASIC computer language and follows the logic presented above. The automated test procedures as applied by the code are: SETUP, SATURATION, CONSOLIDATION, and SHEAR. Pertinent information is entered in the subroutine SETUP as the code is initialized. During execution, the code prompts the operator with options and possible specimen responses. For example, during the subroutine SETUP, pertinent information is input into the code regarding the specimen and test configuration, and the specimen is prepared for the saturation phase of the test. The operator is instructed to provide a name for the file of the test to be performed and is directed by messages appearing on the monitor to open and close appropriate manual valves. The queries appearing on the monitor upon execution of the code are:

a. "Input filename to save data during shear."

b. "Input the initial height of specimen."

c. "Input the initial diameter of specimen."

d. "Input the diameter of the piston."

e. "Input the weight of the piston."

f. "Input the difference in inches betweens transducers 1 and 3."

g. "Input a value for differential between chamber pressure and back pressure (DIFFMAX)."

h. "Input maximum chamber pressure to be used on specimen."

i. "Input consolidation pressure to be used on specimen."

Upon completion of the queries, the following sets of advisories and instructions will appear:

a. "This is the setup portion of the process. Make sure that the stones are bone dry and chamber is completely filled with fluid. Deaired water should be in burettes."

b. "Manually close valves V7, V8, V9 and open valve V10."

c. "Hit ENTER to open valves V2, V3, V5, and V6."

d. "Pressure/vacuum regulators should be connected to V5 and V10."

e. "Apply differential (DIFFMAX) psi to V5 and to pressure lines."

f. "Apply vacuum to chamber through valve V10."

g. "Apply as much vacuum (VMAX) as you can to the soil voids and plumbing lines. Pressure in the chamber is kept (DIFFMAX) psi higher than VMAX. VMAX should be held on the specimen for no more than 10 min."

h. "Hit ENTER to continue."

i. "Using the 3-way valve, switch vacuum line from V5 to V8."

j. "Hit ENTER to continue."

k. "Reduce the vacuum from VMAX to zero. Should end up with (DIFFMAX) psi inside the chamber when vacuum is reduced to zero."

l. "Hit ENTER to continue."

m. "Manually open valves V7 and V9, and switch V8 to E/P2."

n. "You are now ready for saturation!!!!"

o. "Hit ENTER to continue."

Specimen saturation, consolidation, and shear then proceed automatically, as directed by the code in Appendix A, and without the need for operator assistance or presence. Consolidation and shear will be displayed on the monitor screen in real time as *volume expelled* versus *time* and *deviatoric stress* versus *axial displacement*, respectively. It should be noted that procedures within code of Appendix A are explained by comments so that the sequence and progression of events may be followed.

6 Measurement of Volume Change in Unsaturated Specimens

In the effort to be complete, the notion of volume change measurement in unsaturated soil specimens must be considered, and a procedure for handling unsaturated soil is presented here. However, the software presented in Appendix A does not include the capability to handle unsaturated behavior. Determination of volume change during loading is a requirement necessary for studying unsaturated soil strength and behavior. If specialized equipment to allow direct measurement of volume change of unsaturated soil specimens is unavailable, then a rational and defensible procedure to reckon or infer specimen volume change must be developed. Specialized equipment to measure volume change directly in unsaturated soil specimens might consist of a (water) saturated inner chamber around a soil specimen. The difference between the volume of a load piston entering the chamber and the volume of water leaving the inner chamber (as measured in a burette) is the volume change within a soil specimen resulting from loading. Such a procedure requires a specially constructed chamber that may be difficult and inconvenient to use and may not yield precise volume change data. Therefore, the following alternative procedure is offered to allow realistic and rational determination of unsaturated specimen volume change.

Gas Compression to Determine Volume Change

The procedure developed below will be based on measurement of gas pressure induced in soil voids during loading. Certain simplifying assumptions will be made, all of which are believed to be justified and rational and, as such, will not lead to unreasonable or excessively inaccurate results. The assumptions are associated with the ability to measure pore gas pressure precisely and reliably. Each of the four assumptions will be discussed and explained below. A requirement that is fundamental and does not require lengthy discussion is that the specimen under test is perfectly isolated, and there is no liquid or gas loss during loading.

In this development, it will be assumed that:

a. Voids are connected within the volume of the specimen, i.e., there is no occluded void space within the soil specimen.

b. Gas in the soil voids behaves as a perfect gas.

c. The plumbing system and drainage lines associated with the chamber are sufficiently rigid that they do not expand under gas pressure induced as the result of loading applied to the soil specimen.

d. Volume change occurring in the soil specimen compresses the gas in the voids to change the pressure in the gas. Water and soil solids present in the control space/volume are incompressible and therefore do not change volume as the result of loading.

If the degree of saturation in soils under test is less than about 80 to 90 percent, then (gas) voids remain connected at all times (without pore water blockage) and void gas pressure equalization occurs quickly. However, occluded void space may be present in soil specimens with degrees of saturation greater than 90 percent; consequently, loading in such materials must be carried out slowly enough to allow complete gas pressure equalization. The rate of gas diffusion through a soil is much more rapid than the rate of water diffusion. Therefore, if a test is conducted at a rate slow enough to ensure complete pore water pressure dissipation, then, in general, pore gas pressure equalization will be achieved and assumption *a* above is reasonable and valid.

The gas inside the voids of a soil specimen will generally be a mixture of water vapor and air, both of which are well behaved; mixtures of well behaved gases are well behaved. At pressure and temperature levels anticipated in the environment of normal soil testing, departure of the behavior of water vapor and air from that of a perfect gas is so insignificant that assumption *b* above is perfectly reasonable. It should also be noted that at normal pressures and temperatures, gases such as methane and hydrogen sulfide behave as perfect gases so that if a mixture of these gases is present in the voids of soils, behavior does not depart from that of a perfect gas. It is acknowledged that the combined presence of organic matter and certain bacteria in soils results in the generation of certain gases, notably methane and hydrogen sulfide. The rate these gases are generated depends on temperature and other conditions. It will be assumed that gas generated in this manner will not occur rapidly enough to affect the result of strength and properties tests; i.e., all excess gas pressure generated is the result of internal movement of soil particles during shear.

Excess gas pressure that develops in an unsaturated soil specimen is generally no more than a few pounds per square inch. Therefore for piping systems in soil test chambers consisting of copper or steel tubing or even thick-walled nylon tubing, assumption *c* above is justified in that the piping system is rigid against the excess gas pressure it will be expected to contain.

Assumption *d* above is reasonable because gas in the voids of a soil specimen is literally thousands of times more compressible than the water and soil solids that make up the liquid and solid phases of the soil specimen. For example, Poulos (1964) gives a value for the compressibility of quartz as

2.7×10^{-6} cm^2/kg and states that the value for clay minerals is probably greater (meaning that clay minerals are less compressible). Streeter (1966) gives a value of the compressibility of water as 3.125×10^{-6} in.^{2}/lb (4.444×10^{-5} cm^2/kg) at 70°F (21°C). It can be shown using Boyle's law (Wood et al. 1963) that the compressibility of an ideal gas (such as air at normal temperatures and pressures) is the reciprocal of the absolute pressure. It follows then that at normal soil testing pressures (generally less than 115 psia) the compressibility of air is on the order of 8.7×10^{-3} in.^{2}/lb (12.4×10^{-2} cm^2/kg). Therefore, the volume change of soil and water during loading may be neglected without introducing significant error, since air is literally thousands of times more compressible than water or soil solids under the same conditions.

Formulation

The total volume of an unsaturated soil specimen is made up of the respective volumes of solids, water, and gas. Thus,

$$V_t = V_s + V_w + V_a \tag{27}$$

where

V_t = total specimen volume

V_s = volume of soil solids in the specimen

V_w = volume of water in the specimen

V_a = volume of gas in the specimen

The volumes constituting the specimen may be written in terms of weight/volume parameters as

$$V_s = \frac{W_s}{G_s \, \gamma_w} \tag{28}$$

$$V_w = \frac{w \, W_s}{\gamma_w} \tag{29}$$

$$V_a = V_t - \frac{W_s}{\gamma_w} \left[\frac{1}{G_s} + w \right] \tag{30}$$

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where

W_s = weight of solids in specimen

G_s = specific gravity of solids

γ_w = density of water

w = water content expressed as a decimal

It must be noted that water density in this formulation is a function of temperature, and the effect of temperature must be properly taken into account. This is done in Equation 6 above in which an equation developed as a polynomial curve-fit is used to represent water density as a function of temperature.

The combined Boyle's and Charles' gas laws (Wood et al. 1963) may be written

$$\frac{P_i V_i}{T_i} = \frac{P_f V_f}{T_f} \tag{31}$$

where the subscript i indicates the initial state and f the final state. P, V, and T are the absolute pressure, volume, and absolute temperature, respectively.

It is important in this treatment to take the volume of gas in the lines and in the stones into proper account. In order to do this, volume of the lines/tubes and volume of voids in the stones must be determined accurately. For the purpose of this treatment, let V_{sl} be the volume of the lines and volume of voids in the stones. Then

$$\frac{P_i V_i T_f}{T_i P_f} = V_f \tag{32}$$

where

V_f = the final total volume of the voids and piping system

However, since it is assumed that the piping system does not change volume under the pressure change, then

$$V_f = V_{sl} + V_{fv} \tag{33}$$

where

V_{fv} = final volume of gas-filled voids in the specimen volume

Then,

$$\Delta V = V_a - V_{fv}$$ (34)

where

ΔV = change in specimen volume as the result of loading.

By substitution and rearrangement, the equation for ΔV may be rewritten as

$$\Delta V = \left(V_a + V_{sl}\right)\left[1 - \frac{P_i T_f}{P_f T_i}\right]$$ (35)

It should be stated that a requirement for Boyle's and Charles' laws is that the mass of gas in the control volume does not change during the course of the experiment. Therefore, it is specified and emphasized that the piping system must be pressure-tight to the extent that no mass (of gas) enters or leaves the control volume during loading. The indicated control volume is the closed system consisting of the voids of the specimen, the voids in the stones, and the volume of the lines and sensors. If atmospheric pressure changes gradually over the (time) period in which loading and specimen volume change occurs, this pressure change must be taken into account. Provisions have been made to accommodate such variation since the system is equipped with sensors to measure and track barometric pressure. Similarly, provisions have been made (in terms of a temperature sensor provided with the system) to monitor and properly account for variation in ambient temperature during a test.

The applied axial stress at any time during a test is then given by Equation 20 above that contains a term for specimen volume change during loading. It should be noted that the formulation for volume change in an unsaturated specimen was not included in the library of chamber tests that can be performed by the automated system because this is not a standard test. However, the option to take volume change into account in an unsaturated specimen may be quickly and easily accommodated by adding statements to the software to incorporate Equation 35 into the routine. A sensitive and accurate pressure transducer with an appropriate span and capacity to measure pressure to 0.01 psi must be added to the equipment. This transducer will be used to measure induced pore air pressure in the specimen.[1] Software controlling the automated system allows the option to accept output from an additional pressure sensor. The software may be modified to acquire and process data from the pore air sensor and incorporate the data into the control regimen to accommodate the procedure outlined for unsaturated soils.

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[1] P_i is the absolute pressure measured by the pressure transducer at the beginning of the test. P_f is the absolute pressure measured at any time during the test at which volume (change) is desired.

7 Demonstration Tests

Background

Chamber tests were performed to demonstrate the efficacy and operation of the computer-automated system. The demonstration tests were performed on undisturbed clay specimens since tests on clay represent a more severe examination of the system than tests on cohesionless soil. The demands imposed on the automated system are more severe for clay because of the substantially longer response times to achieve saturation and consolidation, and the complexity involved in determining the appropriate rate of deformation for shear.

Controlled rate of strain and rate of stress tests were performed in the unconfined mode[1] to demonstrate the force feedback feature. A consolidated-undrained test performed at a constant rate of strain was performed to test and demonstrate what was essentially all the significant features of the system.

It is useful and meaningful in the presentation of laboratory strength data determined in triaxial compression to present the data in terms of average normal and shear stress. Such representation includes the influence of the three-dimensional stress state imposed in triaxial compression. The representation used in this investigation is that proposed by Lambe and Whitman (1969). The average shear stress, q, and the average effective normal stress, p', defined by Lambe and Whitman (1968), are

$$q = \frac{\sigma_1 - \sigma_3}{2} \tag{36}$$

$$p' = \frac{\sigma_1 + \sigma_3}{2} - \Delta U \tag{37}$$

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[1] Unconfined tests were sufficient to demonstrate the force feedback feature of the system. The addition of pressure in the chamber was unnecessary.

where

σ_1 = applied stress in the axial direction

σ_3 = applied stress in the radial direction

ΔU = induced pore water pressure

Equations 36 and 37 may be expressed in a more functional and practical form using the definition of deviator stress as given by Equation 18. In terms of the deviator stress, Equations 36 and 37 may be written

$$q = \frac{\sigma_a}{2} \tag{38}$$

and

$$p' = \frac{\sigma_a}{2} + \sigma_c - \Delta U \tag{39}$$

where

σ_c = effective applied confining pressure

Data presented in this report are based on use of Equations 38 and 39.

Material

The soil tested in this investigation was an undisturbed medium plasticity clay from the East Atchafalaya Basin Protection Levee (EABPL) system in southeastern Louisiana. The material is a soft brown clay with a liquid limit of 68, a plasticity index of 42, and a specific gravity of 2.74. The soil is classified clay CH in the Unified Soil Classification System (USAE Waterways Experiment Station 1960) and has an average insitu wet density of 1.909 g/cm^3 and an average water content of about 28 percent for a dry density of about 1.503 g/cm^3.

Test Results

Five tests were performed on the EABPL clay described above: two unconfined controlled strain tests, two unconfined controlled stress tests, and one saturated, consolidated, undrained test. The stress, strain, and strength characteristics of the controlled strain tests are summarized in Figure 9, which shows
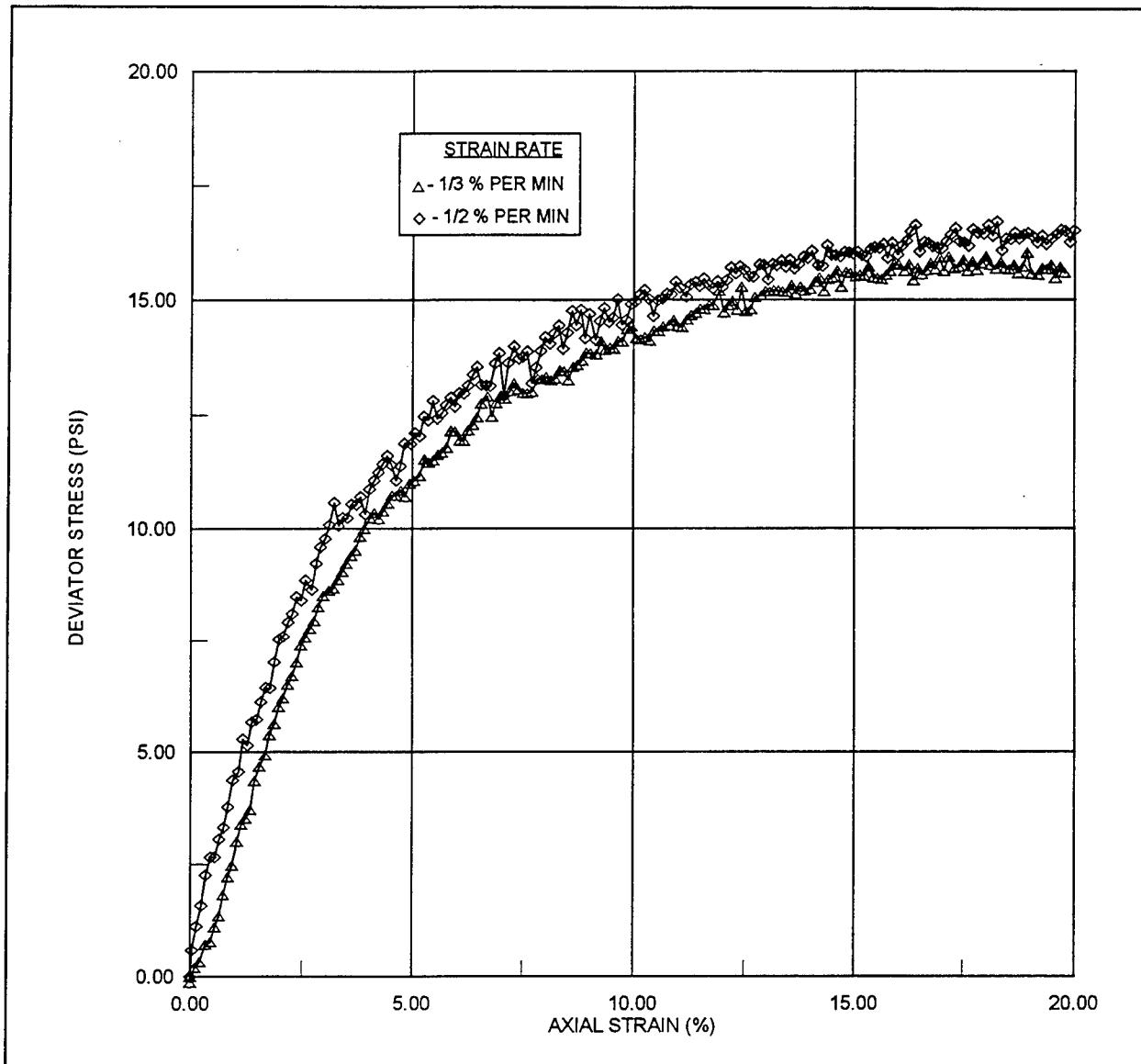
Figure 9. Control strain tests on EABPL clay

that the soil exhibited the plastic stress-strain characteristics that are typical of a soft clay. Figure 10 shows the stress, strain, and strength characteristics of the EABPL soil tested under application of a constant rate of stress. Figure 11 summarizes the behavior of the same soil tested under an effective confining pressure of 25 psi with pore pressure measurement.

Table 2 summarizes the pertinent data for the tests performed. Study of the table and Figures 9 and 10 shows that the constant rate of strain tests produced a slightly higher compressive strength than the constant rate of stress tests. However, the small difference observed is probably due to the fact that the density of the constant rate of strain test specimens was higher (and the water content lower) than that of the constant rate of stress tests.
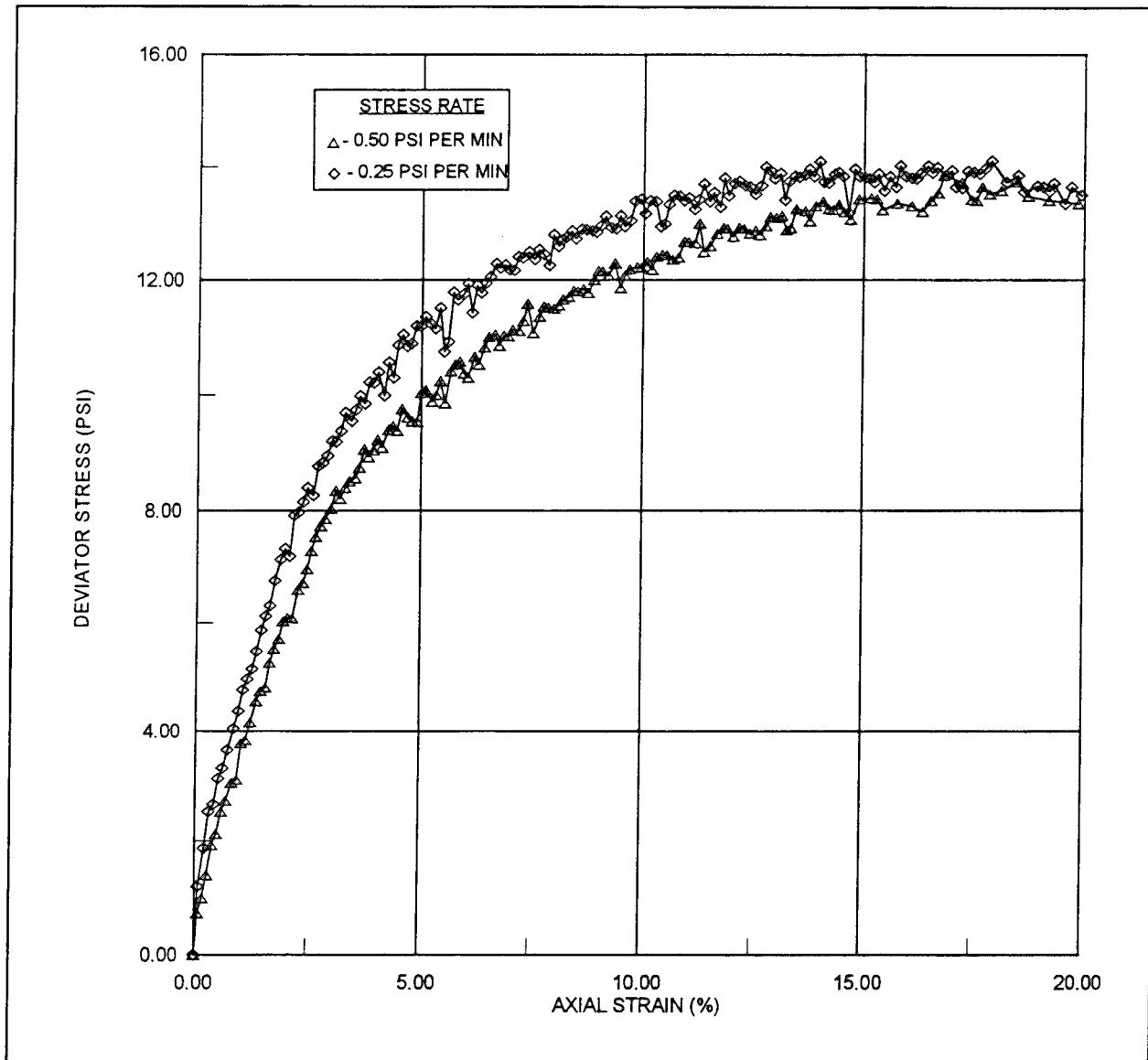
Figure 10. Control stress tests on EABPL clay

The single saturated, consolidated, undrained test with pore pressure mea-surement was performed at constant rate of strain and summarized as test 5 in Table 2. Examination of Figure 11 shows that the test specimen initially developed positive pore water pressure during shear and was, therefore, probably normally consolidated.

Figure 12 shows the plot of the effective stress path in the q-p' space for test 5. The envelope of the q-p' plot is called the K_f line as defined by Lambe and Whitman (1969). This K_f line has slope α which is related to ϕ, the effec-tive angle of internal friction by the relationship

$$\sin \phi = \tan \alpha \tag{40}$$
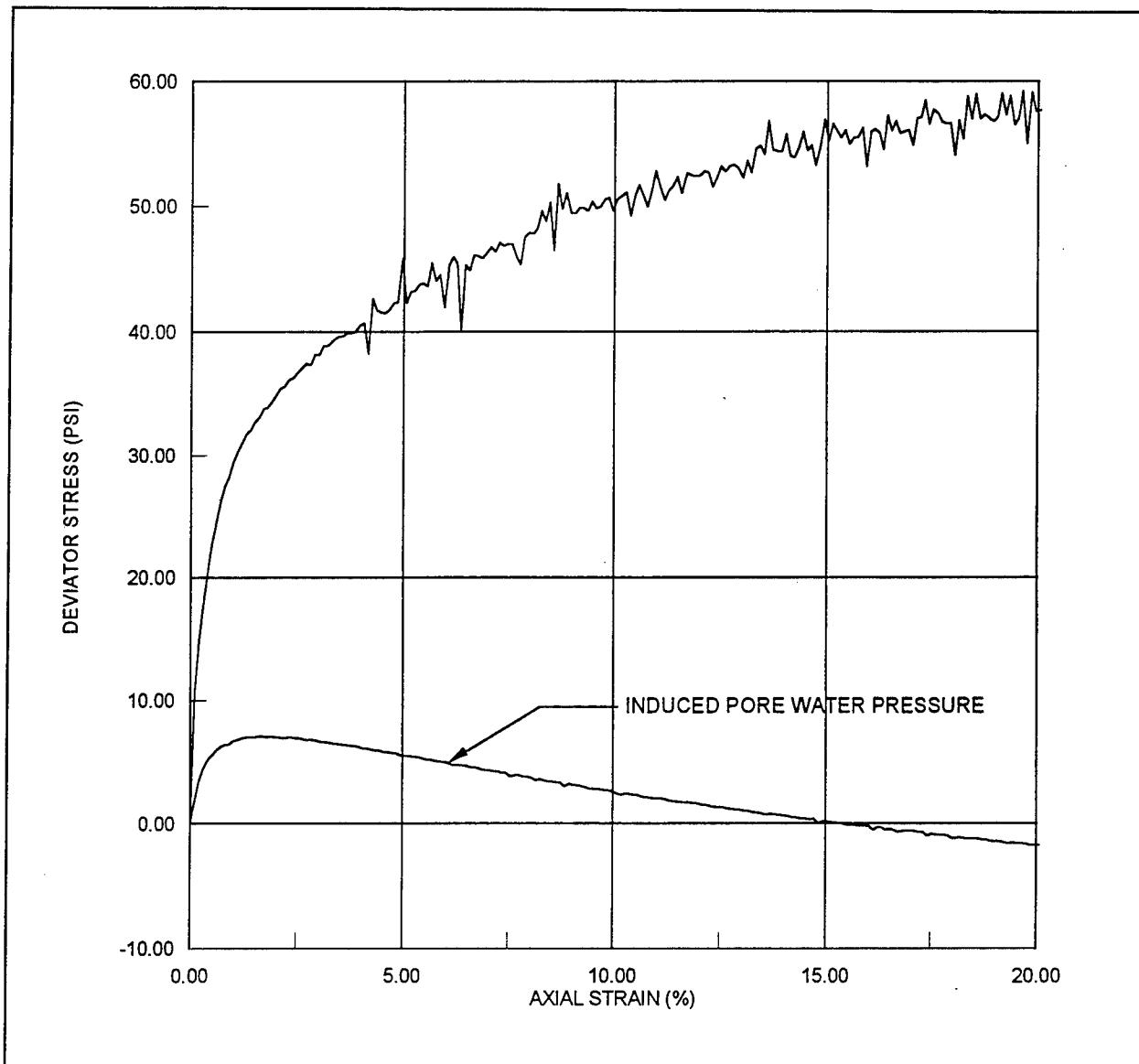
Figure 11. Deviator stress and induced pore water pressure versus axial strain

Table 2
Summary of Tests Performed and Results

Test No. Type	Stress Rate psi/min	Strain Rate Percent/min	Dry Density g/cm³	Water Content Percent	Compressive Strength, psi
1, UNC	-	0.33	1.5353	28.36	15.56
2, UNC	-	0.50	1.5248	28.40	16.34
3, UNC	0.50	-	1.4956	29.70	13.50
4, UNC	0.25	-	1.4911	28.70	13.87
5, CU		0.50	1.5234	27.0	57.73
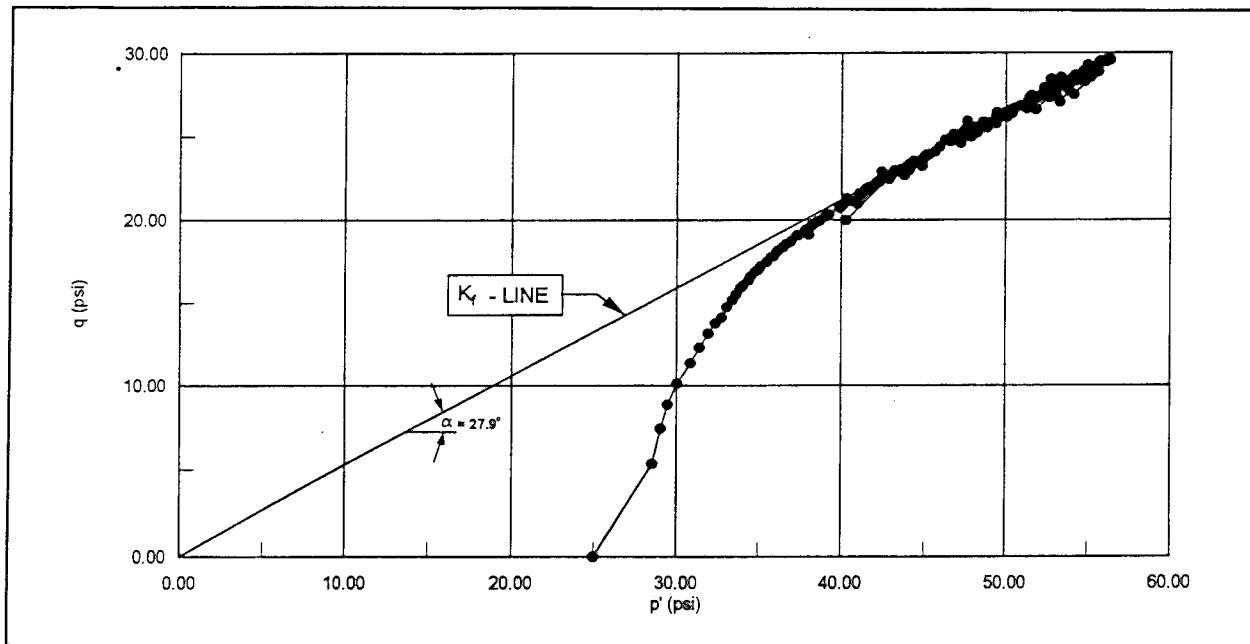
Figure 12. q-p' diagram for EABPL clay tested in consolidated undrained triaxial compression

The α angle was determined from Figure 12 to be 27.9 deg; this range of value is typical for the type of clay tested. Generally, several tests are performed, and the α-line is drawn as the "best straight line fit" through the points at maximum obliquity (points at large strain observed at the end of the test) on the various stress paths. Only one test (stress path) was available for the present demonstration; the points at maximum obliquity produce an α-line that extends through the origin. However, in general, the α-line does not pass through the origin, but intersects the vertical axis at some positive value of average shear stress, q.

Performance of the Computer-Automated System

Tests were performed on the computer-automated chamber test system to demonstrate its efficacy and practicability. The tests were performed on plastic clay, which saturates and consolidates more slowly than granular soils and therefore provides a more difficult test of the system. The system was used to perform a consolidated undrained test with pore pressure measurement, which is a sophisticated test in terms of the operations required for execution.

Some apparent noise was observed in the data during performance of the tests (see Figures 9, 10, and 11). The term "apparent noise" is used because it is not believed to be true noise, but drift in force control due to the marginal ability of a relatively slow computer to keep up with many operations necessary during a test. For example, many of the operations are math-intensive, requiring a large number of computations, and several (nearly simultaneous) operations are required. A relatively slow 386 class computer with a 20 megahertz (MHZ) clock speed was used to execute the software; it is

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suspected that this relatively slow computer may not have been able to keep up with all the (nearly simultaneous) operations required during some of the tests. At this writing, there are Pentium class computers with 200-MHZ clock speeds available at relatively low cost. It is expected that when the automated system is used to perform tests using the newer faster computers, the "noise" will virtually disappear.

The computer-controlled automated system saturated and consolidated test specimens of clay determined an appropriate strain rate from the consolidation data acquired, and sheared the specimen at that strain rate, producing the data presented in Figures 11 and 12. It is therefore concluded that the system performs automated consolidated-drained triaxial soil tests as expected and designed.

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Appendix A
Controlling Computer Code

'The following DECLARE statements declare all of the subroutines.

```
DECLARE SUB SHEAR ()
DECLARE SUB shearmotor (RATE!)
DECLARE SUB conplt ()
DECLARE SUB PLTCON (I!, ii!, iii!)
DECLARE SUB KC (K!, Cv!, T0!)
DECLARE SUB readbalance (vm)
DECLARE SUB zerobalance ()
DECLARE SUB consolidation (bp!, CHP!)
DECLARE SUB INITMOTOR ()
DECLARE SUB ADJUSTMOTOR (ii!, DL!)
DECLARE SUB SATURATION (BVAL!, I, ii)
DECLARE SUB bparam (TCHP!, B)
DECLARE SUB setup ()
DECLARE SUB CALIBRATE ()
DECLARE SUB INIT ()
DECLARE SUB AOT (CHANNEL!, DATTA!)
DECLARE SUB DOT (CHANNEL!)
DECLARE FUNCTION AIN! (ITEM!)
DECLARE FUNCTION DIN! (CHANNEL!)
DECLARE FUNCTION DATCONV! (BYE1!, BYE2!, BYE3!, BYE4!)
DECLARE SUB READSUB (PG!, LOCAT!, HI!, LO!)
DECLARE SUB VV50 ()
DECLARE SUB WRITESUB (PG!, LOCAT!, HI!, LO!)
```

' The following $INCLUDE statement add statements needed for the servomotor.

```
'$INCLUDE: '5638INC.BAS'
```

'The following dimension statements dimension all the arrays.

```
DIM A1(10), B1(10), C1(10), D1(10), CS(10), D0(10), CONSTIME(20), VOLEXP(20)
DIM U(20), DELTAH(20), xcs(49)
```

'The following data statements are used to setup consolidation.

```
DATA .25,.5,1,2,4,8,16,30,60,120,240,480,1440
DATA .1,.2,.3,.4,.5,.6,.7,.8,.9
DATA 1,2,3,4,5,6,7,8,9
DATA 10,20,30,40,50,60,70,80,90
DATA 100,200,300,400,500,600,700,800,900
DATA 1000,2000,3000,4000,5000,6000,7000,8000,9000,10000
```

```
CONST PI = 3.141592654#
CONST ELEV = 195          'Elevation of the test site
```

'The following statements allow the variables to be shared between subroutines.

```
COMMON SHARED STARTADD, A1(), B1(), C1(), D1(), D0(), CS(), U(), DELTAH()
COMMON SHARED DIFFMAX, CPMAX, AREAPISTON, WTPISTON, INITLD, VOLIN, AREAIN, FIN$
COMMON SHARED p1a, p1b, p1c, p1d, p2a, p2b, p2c, SIGCON, RATE, HT0, GAMMAW
COMMON SHARED CONSTIME(), VOLEXP(), AF, BF, CF, DF, ELEV, HEIGHTIN, DIAMETERIN
COMMON SHARED xcs(), vmax, oldlinex, oldliney, oldlinerx, oldlinery, H31, choice
```

'Reads DATA statements for consolidation.

```
FOR I = 1 TO 13: READ CONSTIME(I): NEXT
FOR I = 1 TO 46: READ xcs(I): NEXT
```

' These are coefficients for the voltage-to-pressure transducers.

```
p1a = -4.472544E-08: p1b = 2.556556E-06: p1c = .1002796: p1d = -8.395579E-03
p2a = -4.661531E-06: p2b = .100375: p2c = 1.217104E-02
```

```
STARTADD = 688:  ' UPC607 STARTING I/O ADDRESS
vmax = 100
```

```
2000
```

' These coefficients are for degrees F.

```
AF = -.8216553
BF = 29.67015
CF = -393.7691
DF = 1908.139
```

'End of Declarations

```
'*************************************************************
'*                                                           *
'*              START OF MAIN PROGRAM                        *
'*                                                           *
'*************************************************************
'
' Make sure voltage-to-pressure transducers are initialized to zero and that all valves
' are closed.
CALL AOT(1, 0)
CALL AOT(2, 0)
DOT (0)

    CALL INITMOTOR
    CALL CALIBRATE
    ICP = (AIN(1) + D1(1)) * C1(1)
    IBP = (AIN(3) + D1(3)) * C1(3)

    CLS
    CALL setup
    CALL SATURATION(BVAL, I, ii)
    CALL consolidation(I, ii)
    CALL VV50
    CALL SHEAR
    END
```

```
SUB ADJUSTMOTOR (ii, DL)

'This routine adjusts the motor to offset for the piston uplift.

CONST B.ADDR = &H300        ' Board Address
CONST G.ADDR = &H380        ' Global Address
CONST MODEL = MODEL.5638    ' Model Number
CONST NUMAXES = 1           ' Number of Axes

' AXIS is the number of the axis to be moved
CONST AXIS = 0

' Define the filter parameters
CONST KP = 1000
CONST KI = 0
CONST KD = 900
CONST IL = 0
CONST SI = 0

' Define the trajectory parameters
CONST ACCELERATION = 10000

'ADJUST MOTOR TO COMPENSATE FOR PISTON UPLIFT...

    CHAMBERPRESSURE = ii
    LD = (CHAMBERPRESSURE * AREAPISTON) - WTPISTON
    C1 = (AIN(5) + D1(5)) * C1(5) - INITLD
    DL = LD - C1
    MULT = 1000
    VELOCITY = DL * MULT
    X = FILTER(AXIS, KP, KI, KD, IL, SI)
    X = VELMODE(AXIS, VELOCITY)


END SUB
```

```
SUB bparam (TCHP, BVAL)

'This routine computes the b value of the specimen.

    p1a = -4.472544E-08: p1b = 2.556556E-06: p1c = .1002796: p1d = -8.395579E-03
    p2a = -4.661531E-06: p2b = .100375: p2c = 1.217104E-02

    'close valves V1,V2,V3
    DOT (0)
    tdpt = ((AIN(3) + D1(3)) * C1(3)) - ((AIN(1) + D1(1)) * C1(1))
    T0 = TIMER
    I = TCHP
    I0 = 0
    WHILE I - TCHP <= 5
        I = I0 + RATE * ((TIMER - T0) / 60) + TCHP
        p1 = (p1a * (I ^ 3)) + (p1b * (I ^ 2)) + (p1c * I) + (p1d) + DIFFMAX
        CALL AOT(1, p1)
        LOCATE 3, 30: PRINT USING "CHP = ###.##"; I
        DPT = ((AIN(3) + D1(3)) * C1(3)) - ((AIN(1) + D1(1)) * C1(1))
        LOCATE 5, 30: PRINT USING "CHK = ###.##"; (I - TCHP - DPT + tdpt)

'ADJUST MOTOR TO COMPENSATE FOR PISTON UPLIFT...
        CALL ADJUSTMOTOR(I, DL)


        IF (I - TCHP - DPT + tdpt) > DIFFMAX THEN
            T0 = TIMER
            I0 = I
            WHILE I > TCHP
                I = I0 - RATE * ((TIMER - T0) / 60)
                p1 = (p1a * (I ^ 3)) + (p1b * (I ^ 2)) + (p1c * I) + (p1d)
                CALL AOT(1, p1)
                LOCATE 3, 30: PRINT USING "CHP = ###.##"; I

'ADJUST MOTOR TO COMPENSATE FOR PISTON UPLIFT...
        CALL ADJUSTMOTOR(I, DL)


            WEND

            DOT (7)
            t11 = TIMER
            WHILE TIMER - t11 < 15
                'wait
            WEND
            GOTO ENDBPARAM
        END IF
    WEND
        IF I >= TCHP + 5 AND (I - TCHP - DPT + tdpt) < DIFFMAX THEN
            BVAL = (DPT - tpt) / (I - TCHP)
            BVAL = .85
            IF I > (CPMAX * .75) THEN BVAL = .96
            LOCATE 6, 32: PRINT USING "B =##.##"; BVAL
        END IF
        IF BVAL < .95 THEN
            T0 = TIMER
            I0 = I
            WHILE I > TCHP
                I = I0 - RATE * ((TIMER - T0) / 60)
                p1 = (p1a * (I ^ 3)) + (p1b * (I ^ 2)) + (p1c * I) + (p1d)
                CALL AOT(1, p1)
                LOCATE 3, 30: PRINT USING "CHP = ###.##"; I
'ADJUST MOTOR TO COMPENSATE FOR PISTON UPLIFT...
        CALL ADJUSTMOTOR(I, DL)

            WEND
            DOT (7)
            t11 = TIMER
            WHILE TIMER - t11 < 15
                'wait
            WEND
```

```
                GOTO ENDBPARAM
            END IF
            IF BVAL >= .95 THEN
                T0 = TIMER
                I0 = I
                WHILE I < TCHP
                    I = I0 - RATE * ((TIMER - T0) / 60)
                    p1 = (p1a * (I ^ 3)) + (p1b * (I ^ 2)) + (p1c * I) + (p1d)
                    CALL AOT(1, p1)
                    LOCATE 3, 30: PRINT USING "CHP = ###.##"; I
'ADJUST MOTOR TO COMPENSATE FOR PISTON UPLIFT...
            CALL ADJUSTMOTOR(I, DL)

            WEND
                t11 = TIMER
                WHILE (TIMER - t11) / 60 < .25
                    'wait
                WEND
                T0 = TIMER
                I0 = I
                WHILE I - TCHP <= 5
                I = I0 - RATE * ((TIMER - T0) / 60)
                p1 = (p1a * (I ^ 3)) + (p1b * (I ^ 2)) + (p1c * I) + (p1d)
                CALL AOT(1, p1)
                LOCATE 3, 30: PRINT USING "CHP = ###.##"; I
'ADJUST MOTOR TO COMPENSATE FOR PISTON UPLIFT...
            CALL ADJUSTMOTOR(I, DL)

                WEND
            END IF
                DPT = ((AIN(3) + D1(3)) * C1(3)) - ((AIN(1) + D1(1)) * C1(1))
                BVAL = (DPT - tpt) / (I - TCHP)
                BVAL = .85
                IF I > (CPMAX * .75) THEN BVAL = .96
                LOCATE 6, 32: PRINT USING "B =##.##"; BVAL
                IF BVAL >= .95 THEN DOT (0): GOTO ENDBPARAM
            IF BVAL < .95 THEN
                T0 = TIMER
                I0 = I
                WHILE I < TCHP
                    I = I0 - RATE * ((TIMER - T0) / 60)
                    p1 = (p1a * (I ^ 3)) + (p1b * (I ^ 2)) + (p1c * I) + (p1d)
                    CALL AOT(1, p1)
                    LOCATE 3, 30: PRINT USING "CHP = ###.##"; I
'ADJUST MOTOR TO COMPENSATE FOR PISTON UPLIFT...
            CALL ADJUSTMOTOR(I, DL)

            WEND
                DOT (7)
                t11 = TIMER
                WHILE TIMER - t11 < 15
                    'wait
                WEND

                GOTO ENDBPARAM

            END IF
ENDBPARAM:
END SUB
```

```
SUB CALIBRATE

' This routine is used to calibrate the inputs.

8000 ' @@@@@@@@ CALIBRATION ROUTINE @@@@@@@@@@@
      OPEN "CALSIG.DAT" FOR INPUT AS #1
      FOR I = 1 TO 8
        INPUT #1, A1(I), B1(I), C1(I), D1(I)
      NEXT I
      CLOSE #1
      COLOR 1, 3: CLS : PRINT : PRINT : PRINT
      FLAGME = 1
      INPUT "          DO YOU WANT TO CALIBRATE ? ", Z1$
      IF Z1$ = "Y" OR Z1$ = "y" THEN GOTO 8070
      IF Z1$ = "N" OR Z1$ = "n" THEN GOTO ENDCAL
      PRINT : PRINT "          PLEASE TYPE Y OR N !! ": FOR I = 1 TO 1000: NEXT I: GOTO 8000
8070 CLS : FOR I = 1 TO 1000: NEXT: PRINT
      PRINT "          CALIBRATION FOR TEST CONDUCTED ON AUTOMATED SYSTEM          "
8090 ' ON ERROR 205,8120
      INPUT "          CHANNEL NUMBER? ", C
      IF C < 1 OR C > 8 GOTO 8120
      GOTO 8140
8120 PRINT : PRINT "          INCORRECT INPUT!! PLEASE TRY AGAIN.": GOTO 8090
8140 INPUT "          ARE ZERO AND SCALE FACTOR CORRECT? (Y,N) ", Z1$: IF Z1$ = "Y" OR Z1$ = "y" GOTO 8270
8160 INPUT "          CAL STEP IN ENGINEERING UNITS ? ", CS(C)
      INPUT "          ZERO AMPLIFIER (HIT RETURN) ", Z1$
      FOR I = 1 TO 5: X = AIN(C): NEXT I: R0 = (AIN(C))
      D1(8) = -.092411096#
      INPUT "          INITIALIZE CAL STEP (HIT RETURN) ", Z1$: GOTO 8250
      ' PRINT : PRINT "     WRONG INPUT !! TRY AGAIN !! ": FOR I = 1 TO 2000: NEXT I: CLS : PRINT : GOTO 8130
      A1(4) = 0: B1(4) = 0
8250 RC = AIN(C)
      'PROVISION IS MADE TO FIT A CUBIC EQUATION TO TAKEOUT NONLINEARITES
      'A1 AND B1 ARE THE COEFFICENTS OF THE THIRD AND SECOND DEGREE TERMS
      'WHICH MUST BE DETERMINED BY FITTING
      BOX0 = (A1(C) * R0 ^ 3) + (B1(C) * R0 ^ 2)
      BOXC = (A1(C) * RC ^ 3) + (B1(C) * RC ^ 2)
      C1(C) = (-BOX0 - CS(C) + BOXC) / (R0 - RC): GOTO 8270
      D1(C) = (-BOX0 + (C1(C) * R0)) / C1(C)
      FOR I = 1 TO 1000: NEXT I: PRINT "     YOU DID NOT ZERO !! TRY AGAIN !! ": FOR I = 1 TO 2000: NEXT I:
CLS : PRINT : GOTO 8140
8270 FOR I = 1 TO 1000: NEXT I: CLS : PRINT : PRINT
      PRINT "          CAL STEP = "; CS(C)
      PRINT "          ZERO OFFSET = "; D1(C)
      PRINT "          SCALE FACTOR FOR ENGINEERING UNITS= "; C1(C)
      PRINT
      X1 = AIN(C)
      FOR I = 1 TO 5
      FOR j = 1 TO 1000: NEXT j
      R = AIN(C)
      X = (A1(C) * R ^ 3) + (B1(C) * R ^ 2) + (C1(C) * (R + D1(C)))
      'X = (R + D1(C)) * C1(C)
      IF C = 4 THEN
          PRINT USING "               ####.#### "; X
      ELSE
          PRINT USING "               ####.## "; X
      END IF
      NEXT I
      PRINT
8420 INPUT "          IS MORE CAL DATA REQURIED FOR THIS CHANNEL ? (Y,N) ", Z1$
      IF Z1$ = "Y" OR Z1$ = "y" THEN GOTO 8270
      IF Z1$ = "N" OR Z1$ = "n" THEN GOTO 8460
      GOTO 8420
8460 INPUT "          ARE ZERO AND SCALE FACTOR CORRECT? (Y,N) ", Z1$
      IF Z1$ = "Y" OR Z1$ = "y" THEN GOTO 8500
      IF Z1$ = "N" OR Z1$ = "n" THEN GOTO 8160
      GOTO 8460
8500 INPUT "          DO YOU REQUIRE ADDITIONAL CHANNELS CALIBRATED? (Y,N) ", Z1$
      IF Z1$ = "Y" OR Z1$ = "y" THEN GOTO 8070
      IF Z1$ = "N" OR Z1$ = "n" THEN GOTO ENDCAL
      GOTO 8500
```

```
ENDCAL:
END SUB
```

```
SUB conplt

' This is the plot routine for consolidation.


    XMAX = (LOG(10000) * .434294482#): YMAX = 1000
    XMIN = (LOG(.01) * .434294482#)
    XMIN0 = (LOG(.1) * .434294482#)
    XMIN1 = (LOG(.05) * .434294482#)
    STROLD = 0: STRSOLD = 0
    oldlinex = LOG(.1) * .434294482#
    oldlinerx = LOG(.1) * .434294482#
    oldliney = 0
    oldlinery = 0

    SCREEN 9: COLOR 3, 1: VIEW: CLS
    WINDOW (XMIN - INT(XMAX * .01), YMIN - (YMAX * .15))-((XMAX + INT(XMAX * .3)), YMAX + (YMAX * .12))
    ' DRAW Y AXIS
    PSET (0, 0)
    LINE (0, 0)-(0, YMAX)
    ' DRAW X AXIS
    LINE (XMIN0, 0)-(XMAX, 0)
    LINE (XMIN0, YMAX)-(XMAX, YMAX)
    LINE (XMIN, YMAX / 2)-(XMAX, YMAX / 2)
    ' DRAW TIC MARKS ON Y AXIS
    YTIC = 0
    ' DRAW TIC MARKS ON X AXIS
    XTIC = 0
    FOR I = 1 TO 46
    XTIC = (LOG(xcs(I)) * .434294482#)
    LINE (XTIC, YMIN)-(XTIC, YMAX)
    NEXT I
    ' LABEL Y AXIS
    LOCATE 7, 3: PRINT "Ve"
    NUM = 0
    LOCATE 3, 10: PRINT "0"
    LOCATE 12, 6: PRINT USING "####.#"; vmax
    LOCATE 17, 3: PRINT "U"
    LOCATE 13, 10: PRINT "0"
    LOCATE 22, 10: PRINT "1"
    ' LABEL X AXIS
    LOCATE 1, 31: PRINT "CONSOLIDATION PLOT"
    LOCATE 2, 31: PRINT "     TIME"
    NUM = 0
    LOCATE 24, 11: PRINT ".1";
    LOCATE 24, 24: PRINT "1";
    LOCATE 24, 34: PRINT "10";
    LOCATE 24, 45: PRINT "100";
    LOCATE 24, 56: PRINT "1000";
    LOCATE 24, 67: PRINT "10000";

END SUB
```

```
SUB consolidation (bp, CHP)

' This routine is used to control the consolidation portion of the test.

DOT (38) 'OPEN VALVES V2, V3, V6
    T0 = TIMER
    TCHP = CHP
    I0 = 0
    FLAGU = 0
    WHILE I <= SIGCON - DIFFMAX - 5
        I = I0 + RATE * ((TIMER - T0) / 60) + TCHP
        p1 = (p1a * (I ^ 3)) + (p1b * (I ^ 2)) + (p1c * I) + (p1d) + DIFFMAX
        CALL AOT(1, p1)
        LOCATE 3, 30: PRINT USING "CHP = ###.##"; I
        LOCATE 5, 30: PRINT USING "CHK = ###.##"; (I - TCHP - DPT + tdpt)

'ADJUST MOTOR TO COMPENSATE FOR PISTON UPLIFT...
'        CALL ADJUSTMOTOR(I, DL)
    WEND

    ' GET INITIAL READINGS
    CALL zerobalance
    LVDTINIT = (AIN(4) + D1(4)) * C1(4)
    UINIT = ((AIN(3) + D1(3)) * C1(3)) - ((AIN(1) + D1(1)) * C1(1)) + H31
    ' H31 IS THE HEAD BETWEEN 3 AND 1

    DOT (46)    'OPEN VALVE V4

    'HEAD BETWEEN WATER AND BALANCE AND BOTTOM OF SPECIMEN
    'MUST BE LESS THAN 14 INCHES.
    WHILE ABS(((AIN(3) + D1(3)) * C1(3)) - ((AIN(7) + D1(7)) * C1(7))) > .5
'ADJUST MOTOR TO COMPENSATE FOR PISTON UPLIFT...
        CALL ADJUSTMOTOR(I, DL)

    'WAIT
    WEND

    TC0 = TIMER
    CHKTIME = 1
    T30 = TC0
    CALL conplt
    WHILE CHKTIME < 14
        TCC = TIMER
        WHILE (TIMER - TCC) < 3
        'WAIT
        WEND
        IF TIMERC >= CONSTIME(CHKTIME) THEN
            CALL READBALANCE(VOLEXP(chktime))
            u(CHKTIME) = ((AIN(3) + D1(3)) * C1(3)) - ((AIN(1) + D1(1)) * C1(1)) + H31 - UINIT
            IF U(CHKTIME) < 0 THEN U(CHKTIME) = 0
            DELTAH(CHKTIME) = ((AIN(4) + D1(4)) * C1(4)) - LVDTINIT
            CALL KC(K, Cv, TC0)
            IF VOLEXP(CHKTIME) > vmax THEN
            WHILE VOLEXP(CHKTIME) > vmax
                vmax = vmax + 50
            WEND
                CALL conplt
                FOR OVER = 1 TO CHKTIME
                CALL PLTCON(CONSTIME(OVER), VOLEXP(OVER), U(OVER))
                NEXT OVER
            ELSE
                CALL PLTCON(CONSTIME(CHKTIME), VOLEXP(CHKTIME), U(CHKTIME))
            END IF
            CHKTIME = CHKTIME + 1
        END IF
        UCHK = ((AIN(3) + D1(3)) * C1(3)) - ((AIN(1) + D1(1)) * C1(1)) + H31 - UINIT
        IF UCHK < .5 AND FLAGU = 0 THEN FLAGU = 1: TCHKU = TIMER

        IF (TIMER - TCHKU) / 60 >= 30 THEN
            DOT (14)    'CLOSE VALVE V6
            T00 = TIMER
```

```
            WHILE (TIMER - T00) / 60 < 3
'ADJUST MOTOR TO COMPENSATE FOR PISTON UPLIFT...
'          CALL ADJUSTMOTOR(I, DL)

               'WAIT
               WEND
               UCHK = ((AIN(3) + D1(3)) * C1(3)) - ((AIN(1) + D1(1)) * C1(1)) + H31 - UINIT
               'IF CONDITION ISN'T MET THEN OPEN VALVE AND CONTINUE
               IF UCHK >= .2 THEN FLAGU = 0: DOT (46)'OPEN VALVE 6
               'IF CONDITION IS MET THEN EXIT CONS AND GOTO SHEAR
               IF UCHK < .2 THEN FLAGU = 0: GOTO ENDCONSOL
               FLAGU = 0
          END IF
'ADJUST MOTOR TO COMPENSATE FOR PISTON UPLIFT...
'          CALL ADJUSTMOTOR(I, DL)

      WEND
ENDCONSOL:
LOCATE 1, 20: PRINT "You have reached the end of consolidation"
LOCATE 2, 20: PRINT "      Hit RETURN to continue"
WHILE INKEY$ <> CHR$(13)
'wait
WEND
SCREEN 0: COLOR 1, 3: CLS
END SUB
```

```
SUB INITMOTOR

'This subroutine initializes the servomotor.
' Define some initial constants.
CONST B.ADDR = &H300          ' Board Address
CONST G.ADDR = &H380          ' Global Address
CONST MODEL = MODEL.5638      ' Model Number
CONST NUMAXES = 1             ' Number of Axes

' AXIS is the number of the axis to be moved.
CONST AXIS = 0

' Define the filter parameters
CONST KP = 1000
CONST KI = 0
CONST KD = 900
CONST IL = 0
CONST SI = 0

' Define the trajectory parameters
CONST ACCELERATION = 10000

' Initialize the board
IF INIT.SERVO(B.ADDR, G.ADDR, NUMAXES, MODEL) <> 0 THEN
     PRINT "Board not responding"
     STOP
END IF

X = ABSACC(AXIS, ACCELERATION)

END SUB
```

```
SUB PLTCON (I, ii, iii)

' This routine is used to plot the consolidation data.

    XMIN = (LOG(.1) * .434294482#)
    VIEW (91, 33)-(548, 170)
    WINDOW SCREEN (XMIN, 0)-((LOG(10000) * .434294482#), vmax)
    COLOR 2
      LINE (oldlinex, oldliney)-(LOG(I) * .434294482#, ii)
    oldlinex = LOG(I) * .434294482#
    oldliney = ii
    VIEW (91, 170)-(548, 308)
    WINDOW SCREEN (XMIN, 0)-((LOG(10000) * .434294482#), 1)
    COLOR 2
      LINE (oldlinerx, oldlinery)-(LOG(I) * .434294482#, iii)
    oldlinerx = LOG(I) * .434294482#
    oldlinery = iii

END SUB
```

```
SUB VV50
' This routine computes the time for 50 percent consolidation.
t50 = 0
V0 = VOLEXP(1)
V100 = VOLEXP(CHKTIME)
V50 = (ABS(V100 - V0)) / 2
FOR B = 1 TO CHKTIME - 1
 IF V50 > VOLEXP(B) AND V50 < VOLEXP(B + 1) THEN EXIT FOR
NEXT B
 VB = VOLEXP(B)
 VA = VOLEXP(B + 1)
 TB = CONSTIME(B)
 TA = CONSTIME(B + 1)
 M = (VA - VB) / (log10(TA / TB))
 B = VB - (M * log10(TB))
 t50 = 10 ^ ((V50 - B) / M)
 CALL SHEARMOTOR(0)

END SUB
```

```
SUB readbalance (vm)

' This routine reads the balance and computes a volume from the data.

'COEFFICIENTS FOR COMPUTING DENSITY OF WATER
  ADW = 6.733786E-14
  BDW = -5.30196E-11
  CDW = 1.779546E-08
  DDW = -4.007605E-06
  EDW = 2.430838E-04
  FDW = .9956743
  TF = LOG((AIN(2) + D1(2)) * C1(2))
  f = AF * TF ^ 3 + BF * TF ^ 2 + CF * TF + DF

'THIS ROUTINE IS USED TO READ WEIGHT ON THE BALANCE
  OPEN "com1:2400,e,7,1,CS,CD,DS,RS,LF" FOR RANDOM AS #1
  PRINT #1, "S" + CHR$(13);
  WHILE LOC(1) = 0
  'WAIT
  WEND
  IF LOC(1) > 0 THEN A$ = INPUT$(16, #1): 'PRINT VAL(MID$(A$, 4, 12))
  WR = VAL(MID$(A$, 4, 10))
  pb = (AIN(8) + D1(8)) * C1(8)
  pm = pb * (14.696 / 29.92) * EXP(-.0000361226523# * ELEV)
  RA = 53.34
  'RA = GAS CONSTANT FOR AIR
  'ELEV=SEA LEVEL ELEVATION
  'PB = LOCAL BAROMETRIC PRESSURE IN INCHES OF MERCURY
  PG = (AIN(7) + D1(7)) * C1(7)
  'PG = GAGE PRESSURE INSIDE CHAMBER OR BACK PRESSURE
  GAMMAA = ((PG + pm) * 144) / (RA * (f + 460) * 62.427)
  'GAMMAA = DENSITY OF AIR
  GAMMAW = (ADW * f ^ 5) + (BDW * f ^ 4) + (CDW * f ^ 3) + (DDW * f ^ 2) + (EDW * f) + FDW
  ' F = TEMPERATURE IN FARENHEIT
  vm = (WR + .2233791 - (GAMMAA * 186.2869569#)) / (GAMMAW - GAMMAA)
END SUB
```

```
SUB SATURATION (BVAL, I, ii)

' This routine controls the saturation portion of the test.

    p1a = -4.472544E-08: p1b = 2.556556E-06: p1c = .1002796: p1d = -8.395579E-03
    p2a = -4.661531E-06: p2b = .100375: p2c = 1.217104E-02

CLS
INPUT "Input the rate of PSI/MIN: ", RATE
I = 0: I0 = 0: OLDI = I: TIME$ = "00:00:00": t1 = TIMER
    INITLD = (AIN(5) + D1(5)) * C1(5)
    BEGPOS = ACTPOS(AXIS)
    ii = I + DIFFMAX
    p1 = (p1a * (ii ^ 3)) + (p1b * (ii ^ 2)) + (p1c * ii) + (p1d)
    p2 = (p2a * (I ^ 2)) + (p2b * I) + (p2c)
    IF p1 > 10 THEN p1 = 10
    IF p2 > 10 THEN p2 = 10
    CALL AOT(1, p1)
    CALL AOT(2, p2)
    LOCATE 3, 30: PRINT USING "CHP = ###.##"; ii
    LOCATE 4, 30: PRINT USING " BP = ###.##"; I
    CHAMBERPRESSURE = ii
    LD = (CHAMBERPRESSURE * AREAPISTON) - WTPISTON
    C1 = (AIN(5) + D1(5)) * C1(5) - INITLD
    DL = LD - C1

WHILE ABS(DL) > .5
'ADJUST MOTOR TO COMPENSATE FOR PISTON UPLIFT...
```

```
      CALL ADJUSTMOTOR(ii, DL)
WEND
WHILE ii <= CPMAX
   I = I0 + RATE * ((TIMER - t1) / 60)
   ii = I + DIFFMAX
   p1 = (p1a * (ii ^ 3)) + (p1b * (ii ^ 2)) + (p1c * ii) + (p1d)
   p2 = (p2a * (I ^ 2)) + (p2b * I) + (p2c)
   IF p1 > 10 THEN p1 = 10
   IF p2 > 10 THEN p2 = 10
   CALL AOT(1, p1)
   CALL AOT(2, p2)
   LOCATE 3, 30: PRINT USING "CHP = ###.##"; ii
   LOCATE 4, 30: PRINT USING " BP = ###.##"; I
'ADJUST MOTOR TO COMPENSATE FOR PISTON UPLIFT...
   CALL ADJUSTMOTOR(ii, DL)
   transe = (AIN(1) + D1(1)) * C1(1)
   transd = (AIN(3) + D1(3)) * C1(3)
   IF transd - transe > DIFFMAX THEN
     WHILE transd - transe > DIFFMAX / 2
        'wait
     WEND
     I0 = I
     t1 = TIMER
   END IF
   'PRINT I MOD 5
   IF I - OLDI >= 5 THEN OLDI = I: I0 = I: CALL bparam(ii, BVAL): t1 = TIMER
   IF BVAL < .95 AND I >= CPMAX THEN
     PRINT "MAX BACK PRESSURE WILL NOT SATURATE"
     WHILE INKEY$ = ""
        BEEP
     WEND
   END IF
   IF BVAL >= .95 THEN EXIT SUB
WEND
   IF BVAL < .95 AND ii >= CPMAX THEN
     CLS
     PRINT "         MAX BACK PRESSURE WILL NOT SATURATE"
     WHILE INKEY$ = ""
        BEEP
     WEND
   END IF
END SUB
```

```
SUB setup

' This routine reads the pertinent information about the specimen and prepares the
' specimen for the saturation stage.

CALL AOT(1, -0!): CALL AOT(2, -0!)
DOT (0)
CLS
INPUT "Input filename to save data during shear: ", FIN$
OPEN FIN$ FOR OUTPUT AS #3
INPUT "Input the initial height of specimen: ", HEIGHTIN
INPUT "Input the initial diameter of specimen: ", DIAMETERIN

HEIGHTIN = HEIGHTIN * 2.54      'CONVERT INCHES TO CENTIMETERS
HT0 = ((AIN(4) + D1(4)) * C1(4))
DIAMETERIN = DIAMETERIN * 2.54  'CONVERT INCHES TO CENTIMETERS
AREAIN = PI * DIAMETERIN * DIAMETERIN / 4
VOLIN = HEIGHTIN * AREAIN
INPUT "Input the diameter of the piston: ", DIAPISTON
AREAPISTON = PI * DIAPISTON * DIAPISTON / 4
INPUT "Input the weight of the piston: ", WTPISTON
INPUT "Input the difference in inches betweens transducers 1 and 3: ", DIFFINCHES
H31 = ABS(DIFFINCHES / 27.69)
DOT (0)
PRINT "Input a value for differential between chamber pressure "
INPUT "and back pressure (DIFFMAX): ", DIFFMAX
INPUT "Input maximum chamber pressure to be used on specimen: ", CPMAX
INPUT "Input consolidation pressure to be used on specimen: ", SIGCON
INITLD = (AIN(5) + D1(5)) * C1(5)
CLS
LOCATE 2, 37: PRINT "Setup"
PRINT "    This is the setup portion of the process.  Make sure that the stones"
PRINT "    are bone dry and chamber is completely filled with fluid.  Deaired"
PRINT "    water should be in burettes."
PRINT "    Manually close valves V7, V8, V9 and open valve V10."
PRINT
INPUT "    Hit ENTER to open valves V2, V3, V5 and V6.", A$
DOT (54)
PRINT
PRINT "    Pressure/vacuum regulators should be connected to V5 and V10."
PRINT "    Apply differential"; DIFFMAX; "PSI to V5 and to plumbing lines."
PRINT "    Apply vacuum to chamber through valve V10."
PRINT "    Apply as much vacuum (Vmax) as you can to the soil voids and"
PRINT "    plumbing lines.  Pressure in the chamber is kept"; DIFFMAX; "PSI higher"
PRINT "    than VMAX."
PRINT "    Vmax should be held on the specimen for no more than 10 minutes."
PRINT "    Hit ENTER to continue. "
WHILE INKEY$ <> CHR$(13)
    R = AIN(6)
    I = (A1(6) * R ^ 3) + (B1(6) * R ^ 2) + (C1(6) * (R + D1(6)))
'CALL ADJUSTMOTOR(I, DL)
'
WEND
t1 = TIMER
WHILE (TIMER - t1) / 60 < .1
    LOCATE 20, 37: PRINT USING "###.## MIN."; (TIMER - t1) / 60
WEND
FOR I = 1 TO 7
BEEP: FOR ii = 1 TO 500: NEXT
NEXT
DOT (38)
CLS
LOCATE 2, 37: PRINT "Setup"
PRINT "    Valve V5 is closing."
PRINT "    Using the 3-way valve switch vacuum line from V5 to V8."
INPUT "    Hit ENTER to continue. ", A$
DOT (39)
PRINT "    Reduce the vacuum from VMAX to zero.  Should end up with"
PRINT "    "; DIFFMAX; "PSI inside the chamber when vacuum is reduced to zero."
INPUT "    Hit ENTER to continue. ", A$
DOT (7)
```

```
'  The next operation puts the pressure, "DIFFMAX," on E/P1.
    I = DIFFMAX
    p1 = (p1a * (I ^ 3)) + (p1b * (I ^ 2)) + (p1c * I) + (p1d) + DIFFMAX
    CALL AOT(1, p1)

PRINT "    Manually open valves V7 and V9, and switch V8 to E/P2."
PRINT "    You are now ready for saturation!!!!"
INPUT "    Hit ENTER to continue. ", A$
END SUB
```

```
SUB SHEAR
' This routine controls the shear portion of the test.
DIM init1(8), temp(8), temp1(8)
CLS
ratestrain = (.04 * HEIGHTIN) / (10 * t50)
STPOS = ACTPOS(0)
CALL SHEARMOTOR(ratestrain)
CALL SHEARPLOT
  INLD = (AIN(5) + D1(5)) * C1(5)
  INBOTLD = (AIN(4) + D1(4)) * C1(4)
  WHILE (AIN(5) + D1(5)) * C1(5) - INLD < 1
  WEND
7100 ' START TEST
     LOCATE 3, 41: PRINT "          "
     LOCATE 4, 20: PRINT "                              "
     LOCATE 5, 20: PRINT "                         "
     LOCATE 1, 20: PRINT "              "
     TI1 = TIMER
     TI0 = TI1
     STRSTART = 0
     FOR c = 1 TO 5: init1(c) = (AIN(c) + D1(c)) * C1(c): NEXT c
     DEFL = init1(4)
         ILD = init1(5)

         STRAIN = 0
         STRESS = 0
         CP = init1(1)
         BP = init1(3)
         IPWP = CP - BP
         PWP = CP - BP
         oldstrain = STRAIN
         OLDSTRESS = STRESS
         OLDIPWP = PWP
       OLDQPSI = (STRESS) / 2
       OLDPPSI = OLDQPSI + (CP - PWP)
     FOR IG = 0 TO 1
     SCREEN 9, , IG, CUR: COLOR 3, 1
        LOCATE 1, 15: PRINT USING "              INIT CP,PSI=###.##"; CP
        LOCATE 2, 15: PRINT USING "              BK PRS, PSI=###.##"; BP
     NEXT IG
     GOSUB 7500
7260 FOR c = 1 TO 5: temp(c) = (AIN(c) + D1(c)) * C1(c): NEXT c
7270 FOR c = 1 TO 5: temp1(c) = (AIN(c) + D1(c)) * C1(c): NEXT c
     a$ = INKEY$
     IF a$ = "Q" OR a$ = "q" THEN
     SCREEN 9, , 1, 1: COLOR 3, 1
     LOCATE 4, 15: PRINT "                          "
     LOCATE 5, 15: PRINT "                          "
     LOCATE 6, 15: PRINT "                          "
     LOCATE 4, 15: INPUT "ARE YOU SURE YOU WANT TO QUIT "; a$:
        IF a$ <> "Y" AND a$ <> "y" THEN
           GOTO 7400
        ELSE CALL INITMOTOR: GOSUB 10000: CLOSE #3: EXIT SUB
        END IF
     END IF
7400 IF a$ = "R" OR a$ = "r" THEN
        GOSUB 10000
        PRINT #3, "R"
        GOTO 7100
     END IF
     IF a$ = "C" OR a$ = "c" THEN
        CLOSE #3
        OPEN FIN$ FOR APPEND AS #3
     END IF
     TJCOUNT = TJCOUNT + 1
     IF TJCOUNT >= 10 THEN
        TJCOUNT = 0
        CLOSE #3
        OPEN FIN$ FOR APPEND AS #3
     END IF
     IF a$ = "1" THEN CUR = 0: SCREEN 9, , 0, CUR: COLOR 3, 1
     IF a$ = "2" THEN CUR = 1: SCREEN 9, , 0, CUR: COLOR 3, 1
```

A20

```
        LD = temp1(5)
        CP = temp1(1)
        BP = temp1(3)
        PWP = CP - BP
        STRAIN = (((ACTPOS(0) - STPOS) * .000019685#) / HEIGHTIN) * 100
        CORAREA = AREAIN / (1 - STRAIN / 100)
        STRESS = ((LD - ILD) / CORAREA)
        STREND = STRAIN
        TI2 = (TIMER - TI1) / 60
        IF TI2 > 0 AND ABS(STRAIN) > 0 THEN rate = (STREND - STRSTART) / TI2: TI1 = TIMER: STRSTART = STRAIN

    TMP = (((((ACTPOS(0) - STPOS) * .000019685#) / HEIGHTIN) * 100) - oldstrain
    IF TMP >= .1 THEN
        LD = temp1(5)
        CP = temp1(1)
        BP = temp1(3)
        PWP = CP - BP
        STRAIN = (((ACTPOS(0) - STPOS) * .000019685#) / HEIGHTIN) * 100
        CORAREA = AREAIN / (1 - STRAIN / 100)
        STRESS = ((LD - ILD) / CORAREA)
      GOSUB 7500
      GOTO 7260
    END IF
    SCREEN 9, , 0, CUR: COLOR 3, 1
    LOCATE 3, 15:    PRINT "              RATE =      %/MIN "
    LOCATE 4, 15:    PRINT "         STRAIN =     % "
    LOCATE 5, 15:    PRINT "         STRESS =     PSI "
    LOCATE 6, 15:    PRINT "         IPWP =     PSI "
    LOCATE 3, 15: PRINT USING "          RATE =###.## %/MIN "; rate
    LOCATE 4, 15: PRINT USING "         STRAIN = ##.## % "; STRAIN
    LOCATE 5, 15: PRINT USING "         STRESS = ##.## PSI "; STRESS
    LOCATE 6, 15: PRINT USING "         IPWP =###.## PSI "; PWP - IPWP
    SCREEN 9, , 1, CUR: COLOR 3, 1
    LOCATE 3, 15:    PRINT "              RATE =      %/MIN "
    LOCATE 4, 15:    PRINT "         STRAIN =     % "
    LOCATE 5, 15:    PRINT "         STRESS =     PSI "
    LOCATE 6, 15:    PRINT "         IPWP =     PSI "
    LOCATE 3, 15: PRINT USING "          RATE =###.## %/MIN "; rate
    LOCATE 4, 15: PRINT USING "         STRAIN = ##.## % "; STRAIN
    LOCATE 5, 15: PRINT USING "         STRESS = ##.## PSI "; STRESS
    LOCATE 6, 15: PRINT USING "         IPWP =###.## PSI "; PWP - IPWP
    GOTO 7270
7500 ' OUTPUT TO FILE AND SCREEN
    TI2 = (TIMER - TI0) / 60
    'IF TI2 > 0 AND STRAIN > 0 THEN rate = STRAIN / TI2
    TI3 = (TIMER - TI1) / 60
    IF TI3 > 0 AND ABS(STRAIN) > 0 THEN rate = (STREND - STRSTART) / TI3

    PRINT #3, USING "########.#"; TI2;
    PRINT #3, USING "   #.###"; ((ACTPOS(0) - STPOS) * .000019685#);
    PRINT #3, USING "   ###.#"; LD;
    PRINT #3, USING "   ###.#"; ((AIN(4) + D1(4)) * C1(4)) - INBOTLD;
    PRINT #3, USING "   ###.#"; PWP;
    PRINT #3, USING "   ###.#"; CP;
    PRINT #3, USING "   ###.#"; BP
    SCREEN 9, , 0, CUR: COLOR 3, 1
    XMIN = 0: XMAX = 20: YMIN = 0: YMAX = 50
    VIEW (20, 110)-(320, 340)
    WINDOW (XMIN - INT(XMAX * .15), YMIN - (YMAX * .15))-(XMAX + INT(XMAX * .15), YMAX + (YMAX * .12))
    LINE (oldstrain, OLDSTRESS)-(STRAIN, STRESS)

    'screen 9, , 1, CUR
    XMIN = 0: XMAX = 20: YMIN = -25: YMAX = 100
    VIEW (330, 115)-(630, 335)
    WINDOW (XMIN - INT(XMAX * .15), YMIN - (YMAX * .15))-(XMAX + INT(XMAX * .15), YMAX + (YMAX * .12))
    LINE (oldstrain, OLDIPWP)-(STRAIN, PWP - IPWP)
    OLDIPWP = PWP - IPWP
    oldstrain = STRAIN
    OLDSTRESS = STRESS
    XMIN = 0: XMAX = 100: YMIN = 0: YMAX = 100
    SCREEN 9, , 1, CUR: COLOR 3, 1: VIEW: WINDOW (XMIN - INT(XMAX * .15), YMIN - (YMAX * .15))-(XMAX + INT(XMAX *
.15), YMAX + (YMAX * .12))
```

```
        QPSI = (STRESS) / 2
        PPSI = QPSI + (CP - PWP)
        LINE (OLDPPSI, OLDQPSI)-(PPSI, QPSI)
        OLDQPSI = QPSI: OLDPPSI = PPSI
    IF STRAIN = 15 OR STRAIN >= 20 THEN BEEP
    IF STRAIN >= 20 THEN CALL SHEARMOTOR(0)
    RETURN

10000 ' THIS SETS UP END OF DATA AND SAVES THE SKETCH CODE
        PRINT #3, USING "########.#"; ZERO;
        PRINT #3, USING "    #.###"; ZERO;
        PRINT #3, USING "    ###.#"; ZERO;
        PRINT #3, USING "     ##.#"; ZERO;
        PRINT #3, USING "    ##.##"; ZERO
        RETURN


END SUB
```

```
SUB shearmotor (RATE)

' This routine sets the rate of strain that the specimen is to be sheared.

CONST B.ADDR = &H300          ' Board Address
CONST G.ADDR = &H380          ' Global Address
CONST MODEL = MODEL.5638      ' Model Number
CONST NUMAXES = 1             ' Number of Axes

' AXIS is the number of the axis to be moved
CONST AXIS = 0

' Define the filter parameters
CONST KP = 1000
CONST KI = 0
CONST KD = 900
CONST IL = 0
CONST SI = 0

' Define the trajectory parameters
CONST ACCELERATION = 10000
    'ACCELERATION = (rate / .1) * 3.636405643#
    'X = ABSACC(AXIS, ACCELERATION)
    VELOCITY = 14204.70955# * RATE
    X = FILTER(AXIS, KP, KI, KD, IL, SI)
    X = VELMODE(AXIS, VELOCITY)


END SUB
```

```
SUB SHEARPLOT

' This is the plot routine for shear.


  STROLD = 0: STRSOLD = 0
  FOR IG = 0 TO 2
  IF IG = 0 THEN YMIN = 0: YMAX = 5: XMIN = 0: XMAX = 20
  IF IG = 1 THEN YMAX = 100: YMIN = -25
  IF IG = 2 THEN XMIN = 0: XMAX = 100: YMIN = 0: YMAX = 100
  IF IG = 0 THEN VX1 = 20: VY1 = 110: VX2 = 320: VY2 = 340
  IF IG = 1 THEN VX1 = 330: VY1 = 115: VX2 = 630: VY2 = 335

  SCREEN 9, , 0, 0: COLOR 3, 1

  IF IG = 2 THEN
   SCREEN 9, , 1, 0: COLOR 3, 1: VIEW
  ELSE
   VIEW (VX1, VY1)-(VX2, VY2)
  END IF
  WINDOW (XMIN - INT(XMAX * .15), YMIN - (YMAX * .15))-(XMAX + INT(XMAX * .15), YMAX + (YMAX * .12))
  ' DRAW Y AXIS
  PSET (0, 0)
  LINE (0, YMIN)-(0, YMAX)
  ' DRAW X AXIS
  LINE (0, YMIN)-(XMAX, YMIN)
  ' DRAW TIC MARKS ON Y AXIS
  YTIC = YMIN
  FOR I = 1 TO 5
  YTIC = YTIC + (YMAX - YMIN) / 5
  LINE (XMIN - XMAX * .01, YTIC)-(XMIN + XMAX * .01, YTIC)
  NEXT I
  ' DRAW TIC MARKS ON X AXIS
  XTIC = 0
  FOR I = 1 TO 20
  XTIC = XTIC + XMAX / 20
  IF I = 5 OR I = 10 OR I = 15 OR I = 20 THEN
   LINE (XTIC, YMIN - YMAX * .02)-(XTIC, YMIN + YMAX * .02)
  ELSE
   LINE (XTIC, YMIN - YMAX * .01)-(XTIC, YMIN + YMAX * .01)
  END IF
  NEXT I
  ' LABEL Y AXIS
  IF IG >= 2 THEN
   NUM = YMIN
   LOCATE 23, 2: PRINT USING "###.#"; NUM
   NUM = NUM + (YMAX - YMIN) / 5
   LOCATE 19, 2: PRINT USING "###.#"; NUM
   NUM = NUM + (YMAX - YMIN) / 5
   LOCATE 15, 2: PRINT USING "###.#"; NUM
   NUM = NUM + (YMAX - YMIN) / 5
   LOCATE 11, 2: PRINT USING "###.#"; NUM
   NUM = NUM + (YMAX - YMIN) / 5
   LOCATE 7, 2: PRINT USING "###.#"; NUM
   NUM = NUM + (YMAX - YMIN) / 5
   LOCATE 3, 2: PRINT USING "###.#"; NUM
  END IF
  IF IG = 0 THEN
   LOCATE 23, 2: PRINT USING "###.#"; YMIN
   LOCATE 20, 2: PRINT USING "###.#"; YMAX * .2
   LOCATE 18, 2: PRINT USING "###.#"; YMAX * .4
   LOCATE 15, 2: PRINT USING "###.#"; YMAX * .6;
   LOCATE 13, 2: PRINT USING "###.#"; YMAX * .8;
   LOCATE 10, 2: PRINT USING "###.#"; YMAX
  END IF
  IF IG = 1 THEN
   LOCATE 23, 40: PRINT USING "###.#"; YMIN
   LOCATE 20, 40: PRINT USING "###.#"; YMIN + (YMAX - YMIN) * .2
   LOCATE 18, 40: PRINT USING "###.#"; YMIN + (YMAX - YMIN) * .4
   LOCATE 15, 40: PRINT USING "###.#"; YMIN + (YMAX - YMIN) * .6;
   LOCATE 13, 40: PRINT USING "###.#"; YMIN + (YMAX - YMIN) * .8;
   LOCATE 10, 40: PRINT USING "###.#"; YMAX
  END IF
```

```
   IF IG = 1 THEN
    LOCATE 8, 40: PRINT "INDUCED"
    LOCATE 9, 40: PRINT "PWP, PSI"
   END IF
   IF IG = 0 THEN
    LOCATE 8, 1: PRINT " DEVIATOR"
    LOCATE 9, 1: PRINT "STRESS, PSI"
   END IF
   IF IG = 2 THEN
    LOCATE 1, 1: PRINT "  q, "
    LOCATE 2, 1: PRINT " PSI "
   END IF

   ' LABEL X AXIS
   IF IG >= 2 THEN
    NUM = 0
    NUM = NUM + XMAX / 4
    LOCATE 24, 24: PRINT NUM;
    NUM = NUM + XMAX / 4
    LOCATE 24, 39: PRINT NUM;
    NUM = NUM + XMAX / 4
    LOCATE 24, 54: PRINT NUM;
    NUM = NUM + XMAX / 4
    LOCATE 24, 69: PRINT NUM;
    LOCATE 25, 34: PRINT "   P', PSI   ";
   END IF
   IF IG = 0 THEN
    LOCATE 24, 14: PRINT XMAX * .25;
    LOCATE 24, 21: PRINT XMAX * .5;
    LOCATE 24, 28: PRINT XMAX * .75;
    LOCATE 24, 35: PRINT XMAX;
    LOCATE 25, 15: PRINT "AXIAL STRAIN, %";
   END IF
   IF IG = 1 THEN
    LOCATE 24, 53: PRINT XMAX * .25;
    LOCATE 24, 60: PRINT XMAX * .5;
    LOCATE 24, 67: PRINT XMAX * .75;
    LOCATE 24, 74: PRINT XMAX;
    LOCATE 25, 54: PRINT "AXIAL STRAIN, %";
   END IF

   NEXT IG
   SCREEN 9, , 0, 0: COLOR 3, 1


END SUB
```

```
SUB VV50
' This routine computes the time for 50 percent consolidation.
t50 = 0
V0 = VOLEXP(1)
V100 = VOLEXP(CHKTIME)
V50 = (ABS(V100 - V0)) / 2
FOR B = 1 TO CHKTIME - 1
 IF V50 > VOLEXP(B) AND V50 < VOLEXP(B + 1) THEN EXIT FOR
NEXT B
 VB = VOLEXP(B)
 VA = VOLEXP(B + 1)
 TB = CONSTIME(B)
 TA = CONSTIME(B + 1)
 M = (VA - VB) / (log10(TA / TB))
 B = VB - (M * log10(TB))
 t50 = 10 ^ ((V50 - B) / M)
 CALL SHEARMOTOR(0)

END SUB
```

```
SUB zerobalance

'This routine is used to zero out the balance.

    OPEN "com1:2400,e,7,1,CS,CD,DS,RS,LF" FOR RANDOM AS #1
LOOPER:
T0 = TIMER
    PRINT #1, "T" + CHR$(13);
    WHILE TIMER - T0 < 3
    'WAIT
    WEND
    PRINT #1, "S" + CHR$(13);
    WHILE LOC(1) = 0
    'WAIT
    WEND
    IF LOC(1) > 0 THEN A$ = INPUT$(16, #1): 'PRINT VAL(MID$(A$, 4, 12))
    IF VAL(MID$(A$, 4, 10)) <> 0 THEN GOTO LOOPER
    CLOSE #1
END SUB
```

```
' The following routines deal directly with the data acquisition card used for the tests.
' Since the procedures are independent of this card there is no need to expand on
' routine specific to the card.

FUNCTION AIN (ITEM)
11000 '******************************************************************
      '*                                                        *
      '*          RETRIEVE ANALOG INPUT DATA          *
      '*                                                        *
      '******************************************************************
      '
      ' ********* FETCH CONVERTED DATA TO TRANSFER MEMORY *******
      '
      PG = 3:        ' PAGE 3
      LOCAT = 254:     ' COMMAND REGISTER LOCATION
      LO = 222:        ' COMMAND CODE FOR FETCHING ENGINEERING DATA
      HI = 0:          ' DUMMY VARIABLE
      CALL WRITESUB(PG, LOCAT, HI, LO):  ' WRITE TO UPC607
      '
      '******** FETCH CONVERTED DATA FROM UPC607 INTO PROGRAM *****
      '
      PG = 2:          ' PAGE WHERE DATA RESIDES IN TRANSFER MEMORY
      LOCAT = ITEM * 4: ' STARTING ADDRESS OF DATA FOR ITEM
      CALL READSUB(PG, LOCAT, HI, LO):   ' READ FIRST TWO BYTES OF DATA
      BYE1 = LO
      BYE2 = HI
      LOCAT = (ITEM * 4) + 2: 'SET LOCATION FOR NEXT TWO DATA BYTES
      CALL READSUB(PG, LOCAT, HI, LO):    ' READ NEXT TWO DATA BYTES
      BYE3 = LO
      BYE4 = HI
      DATTA = DATCONV(BYE1, BYE2, BYE3, BYE4):  ' CONVERT TO BASIC VARIABLE DATTA
      AIN = DATTA
      ' RETURN TO MAIN PROGRAM
END FUNCTION
```

```
SUB AOT (CHANNEL, DATTA)
15000 '
      '***********************************************************
      '*                                                        *
      '*          ANALOG OUTPUT SUBROUTINE          *
      '*                                                        *
      '***********************************************************
      IF CHANNEL < 1 OR CHANNEL > 4 THEN GOTO ESUB
      ON CHANNEL GOTO 15100, 15200, 15300, 15400
      ' ************ CHANNEL 1 ********************
15100 IF DATTA < -10 OR DATTA > 10 THEN GOTO ESUB
      IF DATTA < 0 THEN 15150
      HI = INT(DATTA / .256)
      LO = INT(((DATTA / .256) - HI) * 256)
      GOTO 15175
15150 HI = 255 - INT(ABS(DATTA) / .256)
      LO = 255 + INT((256 * ((DATTA / .256) + INT(ABS(DATTA) / .256))))
15175 PG = 3: LOCAT = 228:    ' SET PAGE, LOCATION
      CALL WRITESUB(PG, LOCAT, HI, LO):   ' WRITE TO UPC607
      LO = 1: HI = 0: LOCAT = 238: PG = 3
      CALL WRITESUB(PG, LOCAT, HI, LO)
      GOTO ESUB
      '**************** CHANNEL 2 ***********************
15200 IF DATTA < -10 OR DATTA > 10 THEN GOTO ESUB
      IF DATTA < 0 THEN 15250
      HI = INT(DATTA / .256)
      LO = INT(((DATTA / .256) - HI) * 256)
      GOTO 15275
15250 HI = 255 - INT(ABS(DATTA) / .256)
      LO = 255 + INT((256 * ((DATTA / .256) + INT(ABS(DATTA) / .256))))
15275 PG = 3: LOCAT = 230:    ' SET PAGE, LOCATION
      CALL WRITESUB(PG, LOCAT, HI, LO):   ' WRITE TO UPC607
      LO = 4: HI = 0: LOCAT = 238: PG = 3
      CALL WRITESUB(PG, LOCAT, HI, LO)
      GOTO ESUB
      '**************** CHANNEL 3 ***********************
15300 IF DATTA < 4 OR DATTA > 20 THEN GOTO ESUB
      HI = INT(DATTA / .256)
      LO = INT(((DATTA / .256) - HI) * 256)
      PG = 3: LOCAT = 228:    ' SET PAGE, LOCATION
      CALL WRITESUB(PG, LOCAT, HI, LO):   ' WRITE TO UPC607
      LO = 2: HI = 0: LOCAT = 238: PG = 3
      CALL WRITESUB(PG, LOCAT, HI, LO)
      GOTO ESUB
      '**************** CHANNEL 4 ***********************
15400 IF DATTA < 4 OR DATTA > 20 THEN GOTO ESUB
      HI = INT(DATTA / .256)
      LO = INT(((DATTA / .256) - HI) * 256)
      PG = 3: LOCAT = 230:    ' SET PAGE, LOCATION
      CALL WRITESUB(PG, LOCAT, HI, LO):   ' WRITE TO UPC607
      LO = 8: HI = 0: LOCAT = 238: PG = 3
      CALL WRITESUB(PG, LOCAT, HI, LO)
ESUB:
END SUB
```

```
FUNCTION DATCONV (BYE1, BYE2, BYE3, BYE4)
       '
12000 '**************************************************************
       '*                                                        *
       '*    IEEE Format to BASIC Variable Conversion            *
       '*              Subroutine                                *
       '*                                                        *
       '**************************************************************
       '
       '
       ' Initialize Variables
       SIGN = 1:      ' SET SIGN TO +1
       DATTA = 0:     ' SET DATTA TO 0
       EXPO = 0:   MANT = 0: ' SET EXP, VALUE OF MANTISSA TO 0
       IF (BYE1 = 0) AND (BYE2 = 0) AND (BYE3 = 0) AND (BYE4 = 0) THEN EXIT FUNCTION
       ' Determine value of mantissa
       FOR Z = 0 TO 7:   ' PROCESS LEAST FIRST 2 MANTISSA BYTES
       IF (BYE1 AND 2 ^ Z) <> 2 ^ Z THEN 12625: ' PROCESS NEXT BIT
       MANT = MANT + 1 / (2 ^ (23 - Z)): ' INCREMENT MANT BY BIT VALUE
12625 IF (BYE2 AND 2 ^ Z) <> 2 ^ Z THEN 12635: ' PROCESS NEXT BIT
       MANT = MANT + 1 / (2 ^ (15 - Z)): ' INCREMENT MANT BY BIT VALUE
12635 NEXT Z
       FOR Z = 0 TO 6:   ' PROCESS MOST SIGNIF MANTISSA BYTE
       IF (BYE3 AND 2 ^ Z) <> 2 ^ Z THEN 12655: ' PROCESS NEXT BIT
       MANT = MANT + 1 / (2 ^ (7 - Z)): ' INCREMENT MANT BY BIT VALUE
12655 NEXT Z
       IF (BYE3 AND 128) = 128 THEN EXPO = EXPO + 1: ' PROCESS LSB OF EXP
       FOR Z = 0 TO 6:   ' EXPONENT BYTE
       IF (BYE4 AND 2 ^ Z) <> 2 ^ Z THEN 12680: ' PROCESS NEXT BIT
       EXPO = EXPO + 2 ^ (Z + 1): ' INCREMENT VALUE OF EXP BYTE
12680 NEXT Z
       IF (BYE4 AND 128) = 128 THEN SIGN = -1
       DATTA = SIGN * (1 + MANT) * 2 ^ (EXPO - 127)
       DATCONV = DATTA
ENDDAT:
END FUNCTION
```

```
FUNCTION DIN (CHANNEL)
14500 '
     '*********************************************************
     '*                                                    *
     '*          DIGITAL INPUT SUBROUTINE                  *
     '*                                                    *
     '*********************************************************
     '
     STATUS = 0:       ' INITIALIZE STATUS
     PG = 3
     LOCAT = 224
     CALL READSUB(PG, LOCAT, HI, LO):        ' READ DIGITAL BYTES
     IF CHANNEL > 7 THEN 14570
     STATUS = LO AND (2 ^ CHANNEL)
     IF STATUS > 0 THEN STATUS = 1
     GOTO ENDDIN
14570 STATUS = HI AND (2 ^ (CHANNEL - 8))
     IF STATUS > 0 THEN STATUS = 1
     DIN = STATUS
     GOTO ENDDIN
ENDDIN:
END FUNCTION
```

```
SUB DOT (CHANNEL)
14000 '
      '****************************************************
      '*                                                  *
      '*       DIGITAL OUTPUT SUBROUTINE        *
      '*                                                  *
      '****************************************************
      '
      GOSUB 14400:          ' GET EXISTING DIGITAL DATA
      IF CHANNEL > 255 THEN
         LO = CHANNEL AND 255
         GOTO 14240:   ' HI BYTE OUTPUT
      END IF
      LO = CHANNEL
      GOTO 14250:          ' ENABLE OUTPUTS
14240 HI = CHANNEL - 255
14250 PG = 3:          ' WRITE TO DIGITAL PORTS
      LOCAT = 226
      CALL WRITESUB(PG, LOCAT, HI, LO)
      GOTO ENDL
14400 PG = 3: LOCAT = 224:   ' GET EXISTING DIGITAL DATA
      CALL READSUB(PG, LOCAT, HI, LO)
      RETURN
ENDL:
END SUB
```

```
SUB READSUB (PG, LOCAT, HI, LO)
'*************************************************************
'*               READ SUBROUTINE                           *
'*************************************************************
'
    IF PG > 3 OR PG < 0 THEN GOTO ENDREAD:   ' CK PG FOR VALIDITY
    IF LOCAT > 254 OR LOCAT < 0 THEN GOTO ENDREAD:   ' CK LOCAT FOR VALIDITY
    IF (LOCAT / 2) - INT(LOCAT / 2) <> 0 THEN GOTO ENDREAD: ' CK LOCAT FOR EVEN VALUE
    PAGE = PG + 4 + STARTADD: ' SET ADDRESS OF FOR PAGE
    OUT PAGE, LOCAT: ' ADDRESS OF PAGE
    LO = INP(STARTADD):     ' READ LO BYTE FROM DATA REGISTER
    HI = INP(STARTADD):    ' READ HI BYTE FROM DATA REG + INCREMENT
ENDREAD:
END SUB
```

```
SUB WRITESUB (PG, LOCAT, HI, LO)
10500 '***********************************************************
      '*              WRITE SUBROUTINE                *
      '***********************************************************
      '
      IF PG > 3 OR PG < 0 THEN GOTO ENDWRITE:   ' CK PG FOR VALIDITY
      IF LOCAT > 254 OR LOCAT < 0 THEN GOTO ENDWRITE:   ' CK LOCAT FOR VALIDITY
      IF (LOCAT / 2) - INT(LOCAT / 2) <> 0 THEN GOTO ENDWRITE: ' CK LOCAT FOR EVEN VALUE
      PAGE = PG + 4 + STARTADD: ' SET ADDRESS OF FOR PAGE
      OUT PAGE, LOCAT: ' ADDRESS OF PAGE
      OUT STARTADD, LO:   ' WRITE LO BYTE
      OUT STARTADD, HI:       ' WRITE HI BYTE TO DATA REG + INCREMENT
ENDWRITE:
END SUB
```

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Paul A. Gilbert, Terry V. Jobe

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13. ABSTRACT (Maximum 200 words)
Equipment for performing computer-automated chamber tests (such as triaxial compression tests) was developed in this investigation, including a valve that responds to computer-generated binary signals. In a chamber test, a soil specimen is enclosed in a rubber membrane and subjected to hydrostatic and deviatoric stress under conditions of controlled drainage. After a test specimen is set up inside a pressure chamber and all appropriate test parameters are input into the computer code, the controlling software takes over the test and executes all subsequent activities, including back-pressure saturation, Skempton's B-parameter checks, consolidation, and shear, without further assistance from the operator. Data is acquired, manipulated, and stored during test performance for use in decision making during the test and for plotting and display after the test. In this way operator influence and human error are removed. A consolidated-undrained triaxial test was performed on plastic clay to demonstrate the efficacy of the system and the results discussed. Although not included in the software for performing "routine" tests, procedures were developed and presented in detail for performing tests on partially saturated soil based on measurement of pore air pressure during shear.

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